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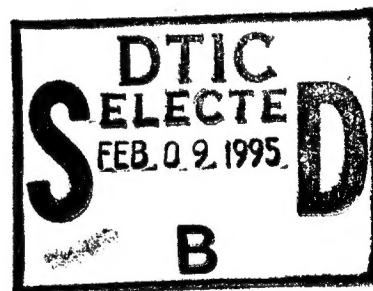
## **Coal Ash Leachate Potential From Stoker Boilers**

by

John F. Cerbus  
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Martin J. Savoie

The Department of Defense (DOD) has 28 installations that use coal and produces about 120,000 short tons of ash per year. Coal ash may be classified as hazardous waste if regulatory tests show leaching of heavy metals and other elements, which would make disposal a more complicated and expensive process. However, the hazardous nature of coal ash remains unclear because current toxicity tests fail to effectively characterize the elemental distribution and chemical solubility of trace metals in the landfill environment. This study investigated the hazardous potential of industrial coal-fired boiler wastes and outlined disposal regulations and feasible disposal options.

Coal and ash samples from three Illinois sites were examined and the leaching characteristics of the ash samples analyzed with specially designed laboratory extraction procedures in association with inductively coupled plasma-atomic emission spectroscopy analysis (ICP-AES). Regulated elements including Ag, As, Ba, Cd, Cr, Hg, Pb, and Se were shown to remain in largely insoluble forms while elements such as B and S leached at higher levels. Experimental results obtained in this research will help operators of coal-fired boilers select coal types and disposal options to curtail the leaching of potentially toxic levels of inorganic contaminants.



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## Foreword

This study was conducted for U.S. Army Center for Public Works (USACPW) under Military Interdepartmental Purchase Request (MIPR) No. W56HZV-89-AC-01, Work Unit R-ARMY-TACOM; "Coal Conversion Strategies for the Army, Installation Technical Assistance." The technical monitor was Qaiser Toor, DAIM-FDF-U, Office of the Assistant Chief of Staff for Installation Management (ACS[IM]).

The work was performed by the Energy and Utility Systems Division (FE) of the Infrastructure Laboratory (FL), U.S. Army Construction Engineering Research Laboratories (USACERL). John Cerbus, of the University of Illinois (UI) Department of Civil Engineering, Urbana, conducted the elemental analysis with facilities provided by the UI Department of Nuclear Engineering. Dr. Sheldon Landsberger is associated with the UI Department of Nuclear Engineering. Donald F. Fournier is Acting Chief, CECER-FE, and Dr. David M. Joncich is Acting Chief, CECER-FL. The USACERL technical editor was William J. Wolfe, Information Management Office.

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# 1 Introduction

## Background

The Department of Defense (DOD) has 28 installations that use coal, about half of which are Army facilities. These plants are primarily used to provide space heating, although several installations use coal all year for industrial processes and co-generation of electricity. Total annual coal consumption for the DOD is about 1.5 million short tons.\* Bituminous coal makes up 99 percent of the coal, and anthracite the remaining 1 percent. The amount of coal consumed at a given site varies from a few thousand tons to about 200,000 tons per year at a cost that ranges from approximately \$25 to \$75 per ton.

The DOD produces about 120,000 short tons of ash per year, a small quantity in comparison to the total production in North America of 50 million tons per year (Warren and Dudas 1989). However, ash disposal costs are significant to large and small coal combustion facilities alike. The cost to dispose of DOD coal ash can vary widely—from no cost to about \$60/ton. (Some installations provide the material at no cost to local highway departments or sell it to structural materials manufacturers.)

While technological improvements in air pollution control have decreased stack emissions, they have also increased elemental concentrations in the ash of coal-fired boilers. Coal ash may be classified as hazardous waste if regulatory tests show leaching of heavy metals and other elements. This classification would complicate land disposal and cause disposal costs to rise. As yet, whether coal ash is too hazardous for landfill disposal remains unclear because current regulatory toxicity tests fail to effectively characterize the elemental distribution and chemical solubility of trace metals in the actual landfill environment.

This research investigated the leaching characteristics of ash samples with specially designed laboratory extraction procedures in association with inductively coupled plasma-atomic emission spectroscopy analysis (ICP-AES). These methods provide a more thorough analysis of coal ash leaching dynamics than the conventional regulatory assessments can provide. Experimental results obtained in this research

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\* 1 short ton = 2000 lb = 907.18 kg.

will help operators of coal-fired boilers select coal types and disposal options to curtail the leaching of potentially toxic levels of inorganic contaminants.

## **Objectives**

The objectives of this research were to investigate the hazardous potential of industrial coal-fired boiler wastes and to outline disposal regulations and feasible disposal options.

## **Approach**

A literature search was performed to determine current disposal regulations and practices. Two laboratory leaching procedures, water-batch and sequential extractions, were performed on six varieties of coal ash. Elemental characterizations were performed on the coal and ash samples. Multi-elemental analytical techniques were used to examine the relationships of elemental levels between coal, ash, and leachates. Results of the analyses were to make recommendations for feasible disposal options.

## **Scope**

This study examined only elemental levels in the coal, ash, and leachates. Organic contaminants such as poly-nuclear-aromatic hydrocarbons (PAHs) were not included. Furthermore, only six ash varieties from three types of coal were examined. It is believed that the data and trends reflected in this study represent typical coals and coal wastes.

## **Mode of Technology Transfer**

It is recommended that the findings of this study be published in the *CPW Digest* and also provided directly to all DOD coal-fired central energy plants.



## 2 Literature Survey

### Coal Ash Composition and Characteristics

Coal ash size, chemical composition, and structure play key roles in ash-water interactions. Coal fly ash is composed of partially combusted solid waste particles with a diameter small enough to be entrained in flue gas. Larger, less homogeneous particle distributions comprise bottom ash. One study determined that 63 percent of the examined fly ash particles ranged from 2 to 50  $\mu\text{m}$  in diameter (El-Mogazi et al. 1988). Bottom ash particles typically range from 10-900  $\mu\text{m}$  in diameter (Merritt 1983). Forms of potentially toxic metals are selectively deposited on the outer surface of coal ash particles (Hopke 1983). Such surface components are not bound to the internal silicate matrix and therefore are readily leachable (Hopke 1983). Three major matrices compose fly ash: silicate glass, mullite quartz, and magnetic spinel (El-Mogazi et al. 1988). Iron oxides such as ferrite and magnetite are common components of the magnetic matrix. It has been found that the magnetic matrix is particularly important in the release of toxic elements (El-Mogazi et al. 1988).

Previous investigations have characterized trace element distributions with respect to ash particle size. Elemental bulk concentrations show systematic enrichment with decreasing particle size (Quann et al. 1990). The larger surface area to volume ratios of the smaller particles account for this increase. Because fly ash tends to be smaller and have higher concentrations, fly ash tends to have a higher potential for leaching

trace elements compared to bottom ash (Norton et al. 1992). Table 1 lists typical median trace element concentrations in coal ash. Some commonly regulated elements, including Ba and Cr, tend to have relatively high concentration levels (Norton, Markuszewski, and Buttermore 1992).\*

Table 1. Median concentrations of trace elements in coal ash.

Concentration (ppm)	Bottom Ash	Fly Ash
<1	Ag, Cd, Hg, Se	Ag, Hg
1-10	As, Mo, Pb, Tl	Cd, Se
11-100	Co, Cu, F, Ni, Zn	As, Co, F, Mo, Ni, Pb, Tl
101-500	B, Cr, Mn, V	B, Cr, Cu, Mn, V, Zn
>500	Ba, Sr	Ba, Sr
Source: Norton et al. 1992.		

\* A list of chemical elements and their abbreviations is included in Appendix A.

It has been shown that the pH of most varieties of coal ash is in the alkaline region when initially mixed with deionized water. The pH of a given ash depends on many factors including coal variety, washing (or other precombustion treatments), combustion characteristics, and any flue gas pollution control technology used.

Porosity and hydraulic properties such as the permeability of ash and soil mixtures may influence land disposal considerations. A study by Page et al. (1979) indicated that the vertical hydraulic conductivity of fly ash is much lower than the lateral hydraulic conductivity. Such low permeability may increase surface run-off and ponding at disposal sites. Computer models have been used to probe landfill leaching, taking into account many factors including evapotranspiration rates, soil type, surface vegetation characteristics, and rainfall.

## **Coal Ash Utilization and Disposal**

Coal waste utilization can include physical and chemical recovery, structural product manufacture, construction fill, and other specialized applications (Norton et al. 1992). In physical and chemical recovery, for example, ash components containing silicon can be physically removed and melted to produce glass products and insulating fibers. Unfortunately, many trace elements are not readily available after combustion since they are fused to internal coal matrices (Norton et al. 1992).

While coal ash can be used in cement and pavement, its leaching properties may be of environmental concern. The pozzolanic properties of coal ash are commonly referred to in describing how the siliceous material can form concrete-like mixtures when combined with water. These properties allow for its use in Portland cement mixtures and in some asphalt pavement applications. These uses can also cause adverse environmental effects due to contaminant leaching. For example, road, dam, and retaining wall construction using coal ash may present surface or groundwater leaching problems (Norton et al. 1992). Atalay and Laguros (1990) found elevated levels of most metals in soil and plant tissue samples near ash-resurfaced highways.

Certain coal varieties are washed prior to combustion to reduce levels of key elements like sulfur. Such coal "cleaning" can alter ash properties, reducing the feasibility of many post combustion uses (Norton et al. 1992).

Most coal ash is destined for land disposal either in landfills or at the site of generation in storage piles or ponds. The inorganic constituents of some types of coal ash may be most toxic to aquatic ecosystems when initially pumped into disposal ponds (Roy et al. 1984).

Water present in a landfill can cause leaching. A soil that has drained until the water held by surface tension is in equilibrium with the gravitational drainage forces is said to have reached field capacity. Water balances and precipitation routing can be performed to determine when and if soils at landfill sites will reach field capacity. A landfill that never reaches field capacity will never generate leachate. This important fact may be included in future regulatory considerations. Therefore, siting a landfill in an arid region, with appropriate hydrogeology and high surface evaporation rate, could be ideal. Often, however, completely ideal sites are not available. Less than optimal sites may be developed provided all regulatory statutes are met. Modern landfills incorporate geotextile membranes, liners, and required leachate collection systems. A more thorough coverage on the subject of landfill design is given in Pfeffer (1992) and Wentz (1989).

## **Hazardous Waste Classification and Regulation**

In 1976, Congress passed the Resource Conservation Recovery Act (RCRA), which defined the term "hazardous waste." The actual regulations that identify hazardous wastes are outlined in Subtitle C. According to 40 FR 261, the U.S. Environmental Protection Agency (USEPA) defines a solid waste as hazardous if it exhibits any of four characteristics (Wentz 1989): ignitability, corrosivity, reactivity, and the toxicity characteristic. The toxicity characteristic is the most applicable to coal waste. Certain wastes such as sludge from electroplating processes are also specifically listed by the USEPA as hazardous (Wentz 1989). Wastes classified as "hazardous" are subject to strict disposal regulations. For example, a waste may be prohibited from disposal in conventional municipal solid waste landfills, forcing disposal in specialized stable waste sites at considerable cost to generators.

The Bevill-Huddleston Amendment to RCRA in 1980 temporarily excluded certain high volume wastes and conventional coal combustion wastes from Federal hazardous waste regulation (Sorini and Jackson 1988). Several states default to the Federal regulations, but many have their own more stringent regulations. In an August 1993 ruling the USEPA determined that:

Large-volume wastes from coal-fired electric utilities pose minimal risks to human health and the environment. Therefore, it is unnecessary to manage these wastes as hazardous (Environmental Fact Sheet EPA530-F-93-014).

The EPA believes that industry and the states should continue to review appropriate management methods for these wastes. Although directed specifically at the utility industry, this ruling should apply to nonutility generators as well. The ruling

recommends that problems be handled on a case-by-case basis and notes that coal wastes will be further assessed under RCRA Subtitle D as nonhazardous wastes.

The Electric Power Research Institute (EPRI) reported that one coal utility, Southwestern Electric Power Co., saved \$118 million from the nonhazardous designation, which allowed the company to continue selling about 200,000 tons of fly ash per year for road construction and other beneficial uses (*Innovators With EPRI Technology* 1993). At present, the Federal exemption is still valid under Subtitle C, although results from pending studies may prompt further regulatory change.

The current regulatory benchmark test designed to identify wastes likely to leach hazardous concentrations of certain toxins into groundwater, is the toxicity characteristic leaching procedure (TCLP). The test was designed to simulate leaching actions that occur in landfills. If extract concentrations of certain metals or organic compounds exceed regulatory limits, the waste is classified as hazardous. The TCLP replaced the extraction-procedure (EP) toxicity test standard in 1990, which was inadequate for organic compounds (Bishop 1990). With the implementation of the TCLP, the regulatory focus is now on environmental impact, behavior, and leachability of contaminants instead of the presence of contaminants in waste (Bishop 1990). Table 2 lists the maximum allowable inorganic contaminant concentrations in a given TCLP extract. The contaminants in Table 2 are referred to as the TCLP elements.

The TCLP uses acetic acid as the extractant and is run for 18 hours in a closed vessel. Acetic acid is a common product of the anaerobic degradation processes found in municipal solid waste (MSW) landfills. The TCLP test, however, fails to effectively characterize the elemental distribution and chemical solubility of coal ash in an ash monofill environment where leaching conditions very likely differ from test conditions. For example, an ash monofill would not have an embedded source of acetic acid.

Waste stabilization may be used to reduce leaching in conjunction with land disposal. Such processes attempt to immobilize a waste within an inert matrix, e.g., by using

**Table 2. Median concentrations of trace elements in coal ash.**

Concentration (ppm)	Bottom Ash	Fly Ash
<1	Ag, Cd, Hg, Se	Ag, Hg
1-10	As, Mo, Pb, Ti	Cd, Se
11-100	Co, Cu, F, Ni, Zn	As, Co, F, Mo, Ni, Pb, Ti
101-500	B, Cr, Mn, V	B, Cr, Cu, Mn, V, Zn
>500	Ba, Sr	Ba, Sr

Source: Norton et al. 1992.

Portland cement, specialized polymers, and plastics as binding agents (Wentz 1989). Such processes are often cost prohibitive. The TCLP may be implemented, following stabilization, to gauge the success of such processes (Biedry 1990).

## Elements of Environmental Concern

Certain elements deserve special attention when land disposal of wastes is considered, since natural chemical weathering processes and soil leaching can lead to contamination of soils and drinking water supplies. Of special interest are the eight regulated TCLP metals and metalloids: Ag, As, Ba, Cd, Cr, Hg, Pb, and Se. Furthermore, B, Be, Mo, S, Sb, Sn, Sr, and V levels in leachates may prompt concern due to possible adverse health effects.

Table 3 lists some inorganic contaminants and possible consequences of exposure. It should be stressed that slightly elevated levels of certain elements may not present an immediate threat to animal life, but may be highly toxic to soil microbial communities and surface vegetation. For example, El-Mogazi et al. (1988) described a coal ash that leached boron levels toxic to plants. Many of these elements are ordinarily found in soil at trace levels. Table 4 lists typical concentrations of trace metals in average soil.

Water percolating through a landfill can absorb soluble inorganic forms, e.g., sulfides and chlorides. Metals present in relatively insoluble forms require leaching agents containing acids, bases, oxidizing agents or mixtures of these (Zumdahl 1993). A leaching solution with a pH of less than 5.0 can lower the oxidation-reduction (redox) potential to a range where many metals are soluble (Pfeffer 1992). Therefore, it is desirable to maintain landfill (leachate) pH at near neutral levels.

The polarity of the water molecule is the basis for water's solvent properties and so is a key ingredient in leaching processes. Snoeyink and Jenkins (1980) describe the solvent property of water:

The minerals that make up the earth's crust are largely inorganic solids in which positively charged and negatively charged ions exist in a lattice structure, attracted to each other by electrostatic bonds. Water, with its dipolar character, has the power to surround a positively charged ion with the negatively charged part of its molecule (or conversely surround the negatively charged crystal ion with the positively charged part of its molecule), thereby isolating the ion from its surrounding ions and neutralizing the forces of attraction that maintain the integrity of the crystal structure. The ion, surrounded (or hydrated) by water molecules, can leave the crystal lattice and move out into solution—it becomes a dissolved ion (Snoeyink and Jenkins 1980).

Table 3. Inorganic contaminant concerns.

Element	Concern	Source
Ag	Permanent discoloration of skin and eyes	1
As	Digestive and cardiac abnormalities	1
Ba	Cardiac, bladder and gastrointestinal disorders	1
Cd	Liver and renal cortex accumulation	1
Cr	Respiratory and dermatologic effects	1
Hg	Mental disorders, ataxia, and vision impairment	1
Pb	Nervous system and kidney disorders	1
Se	Plant uptake and toxicity to grazing animals	1
Be	Osteosarcomas in laboratory animals	2
Mo	Liver and kidney damage, weight loss	2
V	Lung effects from inhalation; oral toxicity is unconfirmed	2
1:Viessman and Hammer 1985; 2:Tate and Arnold 1992.		

Table 4. Trace elements in average soil.

Element	Mean	Range
Ag	0.1	0.01-5
Al	7.1%	—
As	6	0.1-40
B	10	2-100
Ba	500	—
Cd	0.06	0.01-0.7
Cr	100	5-3000
Cu	20	2-100
Fe	38000	7000-550000
Hg	0.03	0.01-0.3
Mn	850	100-4000
Pb	10	2-200
Se	0.2	0.01-2
Sn	10	2-200
Sr	300	—
Zn	50	—
Source: Bowen 1966.		
* All concentrations in mg/g except where noted..		

Arsenic and selenium are naturally occurring elements that can be toxic at high concentrations. Health effects attributed to As include skin cancer, liver cancer, and circulatory disorders. Aqueous Se can be acutely toxic at all levels of the food chain (Inorganic Contaminants Research Committee 1993). Selenium is the toxin associated with the "blind staggers" of cattle grazing on seleniferous vegetation (Viessman and Hammer 1-985).

Cadmium occurs naturally in zinc ores. Health effects due to cadmium can be both acute and chronic since the heavy metal has been shown to accumulate in the liver and renal cortex (Viessman and Hammer 1985).

Table 5 lists some constituents of typical groundwater. The groupings are those of Freeze and Cherry (1979). The elements

Table 5. Dissolved inorganics in groundwater.

Minor Constituents (0.01-10.0 mg/L)	Trace Constituents (less than 0.1 mg/L)
Boron Iron Potassium Strontium	Antimony Arsenic Barium Beryllium Cadmium Chromium Lead Molybdenum Selenium Silver Tin Vanadium
Source: Freeze and Cherry 1979.	

B and Sr are listed as minor constituents while Be, Mo, Sb, Sn, V, and the TCLP elements fall under the "Trace" category.

Some of the subtleties of groundwater geochemistry warrant discussion at this point. First of all, solubility, adsorption, degradation, concentration gradients, redox potential, and many other factors influence contaminant mobility. Electrical charge differences on clay particles in soils encourage the adsorption of ions from solution.

Positive ions (cations) are more readily adsorbed than negatively charged ions (anions). This is due to the predominance of negative charges on the clay surfaces. Cations in solution can exchange for monovalent cations on the clay. Therefore, in addition to the benefit of low permeability, clay soils can attenuate the movement of metal ions.

The concentration and speciation of trace metals in groundwater is a result of complicated chemical and physical interactions. Trace metals, such as Ag, Cd, Cr, Cu, Hg, Mn, and Zn, usually occur in groundwater at concentrations well below 1 mg/L (Freeze and Cherry 1979). This is due in part to solubility limits and adsorption to clay particles or to iron and manganese oxides. Trace metals are known to form complex species with inorganic anions present in groundwater (sulfate, bicarbonate, chloride, etc.). Chemical analyses yielding total trace metal concentrations do not provide information concerning speciation/complexation and, therefore, the mobility of the metals involved. Through rigorous application of equilibrium thermodynamics, the concentrations of many inorganic species in groundwater can be calculated from total concentration data. This task, however, is best handled by geochemical computer models. Metals may be present as free ions, complexes with hydroxides/organics, or as insoluble species.  $\text{BaSO}_4(\text{s})$  is an example of an insoluble precipitate. The pH of most groundwater is in the range of 5 to 8 (Wentz 1989). As pH increases, the percent of the total concentration existing as hydrolyzed species increases (Freeze and Cherry 1979). The various adsorption and precipitation processes tend to keep levels of trace metals low in groundwater. Furthermore, according to Freeze and Cherry (1979):

In nonacidic groundwaters with high concentrations of dissolved inorganic carbon, solubility of carbonate materials will, if equilibrium is achieved, maintain concentrations of metals such as cadmium, lead, and iron at very low levels ...

provided that excessive amounts of complexing substances are not present in the water.

## **Elemental Analysis**

Thorough analysis of trace elements present in ash and leachate usually involves the use of atomic emission spectroscopy. Multi-elemental techniques in which many elements can be analyzed simultaneously are the most desirable. Neutron activation analysis (NAA), X-ray diffraction, and inductively coupled plasma atomic emission spectroscopy (ICP-AES), methods have been employed to this end. Methods are sometimes used jointly for complementary checks as elemental sensitivities vary.

## **Neutron Activation Analysis**

Neutron activation analysis (NAA) determines concentrations based on measurement of induced radioactivity. Emitted gamma-ray energy spectra characterize and quantify the individual elements present. Solid and liquid samples can be examined with low detection limits for many trace elements. Furthermore, the presence of organic compounds in a sample will not interfere with NAA.

## **Inductively Coupled Plasma—Atomic Emission Spectroscopy**

Due to very high source temperatures and large numbers of available spectral lines, ICP analysis can determine elements not normally detected by atomic absorption (e.g., rare earth elements) (Ingamels 1986). During ICP analysis, free atoms from a liquid sample are sprayed through a nebulizer into a high temperature plasma. A radio frequency coil provides the necessary current to maintain the plasma at about 9000K. A diffraction grating separates and directs individual wavelengths of the resulting atomic emissions to photo-multiplier tubes. Individual elements can then be characterized and quantified (Ingamels 1986). The high temperatures attained in the sample induction zone improve breakdown of the sample, atomization, and excitation (Van Loon 1985). A typical ICP detection system block diagram is shown in Figure 1. Method detection limits are sufficiently low for most trace metal analysis if the requisite quality assurance and quality control practices are employed. The method detection limit (MDL) is defined as the minimum concentration of a substance that can be identified, measured, and reported with 99 percent confidence that the analyte concentration is greater than zero. The limit is determined by replicate analysis of a sample containing the analyte.



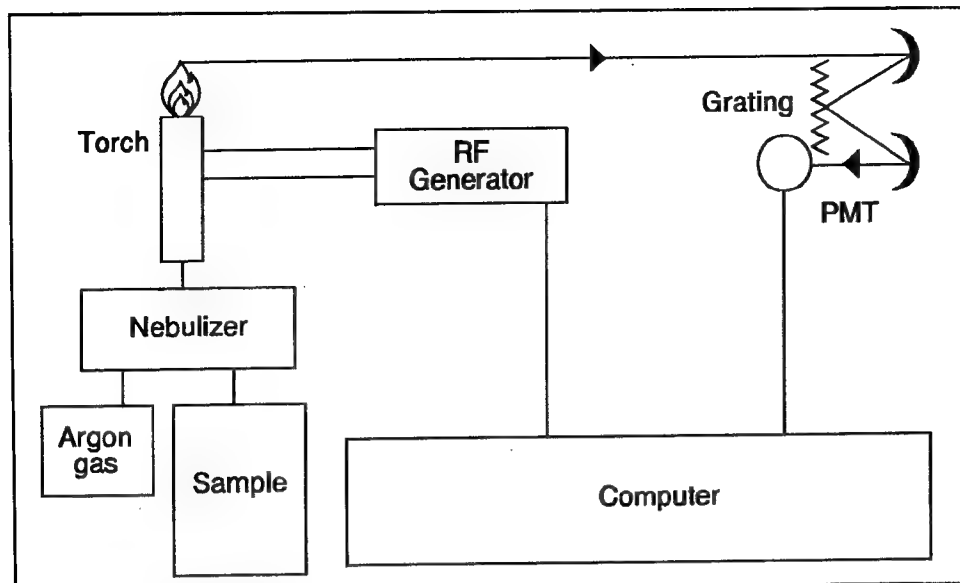


Figure 1. ICP detection system.

## Leaching Methods

Workers have employed a variety of methods to examine coal ash leaching. Techniques range from performing laboratory scale extractions to monitoring large outdoor test plots of ash. Some researchers use aggressive approaches to leach as much from the ash as possible. These methods most likely involve leaching conditions that would not be encountered naturally. The preferred strategy is to construct a leaching scheme that simulates yet accelerates the natural behavior of ash buried in landfills (Buchholz 1993).

Some researchers try to mimic a landfill environment as much as possible. Lysimeters or outdoor test plots may be employed to better simulate natural leaching. Unfortunately, these methods are usually slow since it can take several months to complete a single extraction (Buchholz 1993). Lysimeter extraction tests, performed with columns of ash and soil, may be subject to uncharacteristic channeling and surface tension problems along the inside column wall. Outdoor test plot studies are perhaps the most realistic but usually require years of continuous monitoring.

Commonly performed laboratory leaching procedures include EP and TCLP tests, water batch extractions, and sequential extractions. The EP and TCLP regulatory leaching tests were not specifically designed to measure the behavior and toxicity of coal ash. The use of acetic acid as an extractant in the above tests may not represent the leaching conditions found in an ash monofill.

The long-term washing of coal ash can be simulated with water batch extraction techniques. Varying liquid-to-solid (LS) ratios . . . employed as the ash is agitated in water. Samples for each LS ratio are taken over consecutive days. Temperature and pH may be controlled throughout if desired. By carefully selecting extractants, LS ratios, and sample analysis techniques, the researcher can study many conditions as well as both short- and long-term washing.

Sequential extraction techniques use selective reagents to partition trace elements into chemical forms likely to be released under various environmental conditions (Buchholz 1993). Researchers have successfully applied a sequential extraction procedure developed by Tessier et al. (1979) to coal ash and other geologic samples. A qualitative characterization of the chemical speciation of trace metals can be inferred from the analysis. The elements can be identified as belonging to one of several categories or chemical forms: readily exchangeable, bound to carbonates or surface oxides, bound to iron and manganese oxides, and bound to organic matter (Tessier et al. 1979). Using sequential techniques gives the researcher a significant improvement in characterization over the regulatory extraction tests that do not examine chemical forms.

## **Leachate Composition**

Previous studies have identified several trends in the composition of coal ash leachates. First of all, the pH of most leachates was alkaline in the 8 to 12 range. Leachates extracted with more acidic solutions seem to accordingly have higher metal concentrations (Buchholz 1993). Furthermore, fly ash samples usually leach at higher levels than corresponding bottom ash samples.

Water batch extractions usually show large concentration peaks for readily leachable elements in the early, low-LS-ratio samples. Elements more effectively bound to the internal matrices may not leach out until the higher LS ratios are reached. Wadge and Hutton (1988) found selenium to be highly susceptible to leaching despite relatively low levels in ash samples. Furthermore, Wadge and Hutton (1987) found that most of the Cd and Pb ended up in the residual, implying a low solubility for these metals in a landfill environment. Cd, however, was shown to be more mobile. Finally, Wadge and Hutton (1987) described a "marked uptake of Cd and Pb by crop plants grown on fly ash amended soils," indicating potential leaching of these contaminants.

Warren and Dudas (1988) used acidic conditions in lysimeters to leach over 80 percent of the As and B from fly ash samples. Remaining trace elements, for the most part, were designated as not likely to be readily mobilized in acidic leaching conditions

(Warren and Dudas 1988). Furthermore, Warren and Dudas (1988) suggested that Sb, V, Th, and Cr had undergone adsorption or coprecipitation by iron compounds, or had otherwise remained in insoluble forms.

### 3 Experimental Methods and Results

#### Research Objectives

Recent state environmental agency concern about the classification of coal-fired boiler wastes may result in substantial cost increases for waste disposal. A given coal ash may be classified and regulated as a hazardous waste due to its potential for leaching of heavy metals. Experimental results of laboratory leaching studies may help operators of coal-fired boiler industries select coal types and disposal options to curtail the leaching of toxic levels of inorganic contaminants. This research performed two types of laboratory leaching procedures, water-batch and sequential extractions, on six ash samples to examine the leaching dynamics and relationships of elemental levels between coal, ash, and leachates.

#### Coal and Ash Sample Origins

The coal and ash samples for this study were provided by the U.S. Army Construction Engineering Research Laboratories (USACERL). The samples originated from Abbott Power Plant (Champaign, IL), Chanute Air Force Base (Rantoul, IL), and the Rock Island Arsenal (Rock Island, IL). Bottom and fly ash samples from each site were provided for a total of six ash varieties. (However, the Abbott fly ash sample was actually a mixture of bottom and fly ash.)

#### Coal Characteristics

Elemental concentrations in the coal samples were determined using neutron activation analysis (NAA) and X-ray fluorescence (XRF) methods. Appendix B lists complete results, including detection limits and uncertainties. Figure 2 gives an elemental characterization of the three coal varieties, performed by NAA and XRF.

The elemental concentration in the coal varied for each element and for each coal tested. Si, S, Fe, Al, and Ca were the most abundant elements present. The Abbott coal sample contained more than 10 times the Cl of the Chanute sample. The Chanute sample contained the highest Sr concentration (86 ppm). Sr levels in the Rock Island

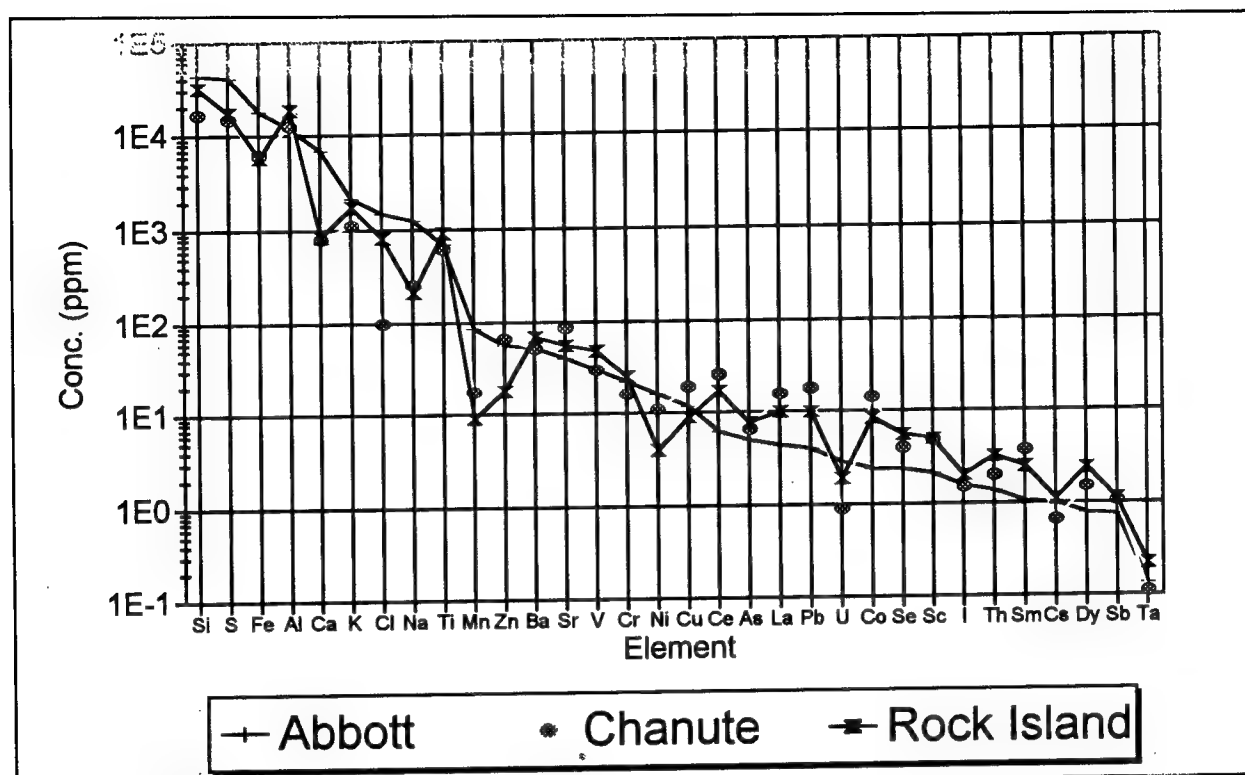


Figure 2. Elemental characterization of coal samples.

and Abbott coal were 55 ppm and 41 ppm, respectively. U levels were highest in the Abbott sample (2.9 ppm) with Rock Island and Chanute levels at 1.9 ppm and 0.9 ppm, respectively. Abbott coal contained the highest level of sulfur, 4.1 percent (41000 ppm), of the three varieties (Rock Island, 1.7 percent, and Chanute, 1.4 percent). With the exception of aluminum, the Abbott coal seemed to have elevated levels of the 10 most abundant elements (Si through Mn in Figure 2). This trend was somewhat reversed for the elements present at lower levels.

Figure 3 shows the levels of the TCLP elements in the coal samples. Cadmium levels were not determined in the coal but were examined in the leachate analysis. Levels of Hg and Ag were below detection limits for all coal samples. Ba and Cr were the most dominant TCLP elements.

### Ash Characteristics

USACERL provided bottom ash and fly ash samples of the three coal varieties in sealed, 5-gal\* buckets. NAA and XRF methods were used to characterize the ash. Detailed data including uncertainties and detection limits are listed in Appendix C.

\* 1 gal = 3.78 L.

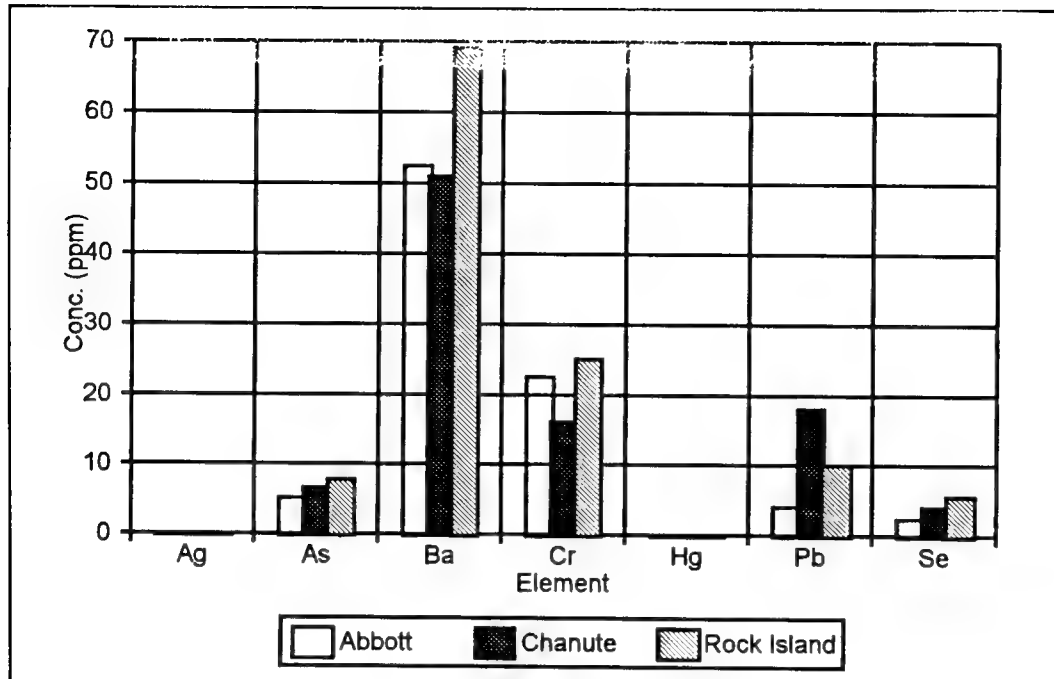


Figure 3. TCLP elements in coal sample.

## Bottom Ash

Figure 4 shows an elemental characterization of the three bottom ash varieties. The most abundant elements include Si, Fe, Al, Ca, K, Na, and S. Sulfur levels ranged from 0.25 percent (Rock Island) to 0.63 percent (Abbott). The bottom ash sulfur levels were significantly lower compared to the coal levels.

Chlorine levels ranged from 9.5 ppm (Chanute) to 24.6 ppm (Abbott). These levels were significantly lower than the coal chlorine levels. Strontium levels ranged from 223 ppm (Abbott) to 547 ppm (Chanute). The bottom ash strontium levels were elevated compared to the coal levels. Levels of uranium in the bottom ash ranged from 7.4 ppm (Chanute) to 24.7 ppm (Abbott). Uranium concentrations were higher in the bottom ash than in the coal samples.

Figure 5 shows levels of the TCLP elements in the bottom ash samples. Hg and Ag levels were below detection limits for all samples. Cadmium levels were not determined. Ba and Cr were the major TCLP elements present. Additionally, concentrations of the TCLP elements were higher in the bottom ash than in the coal samples.

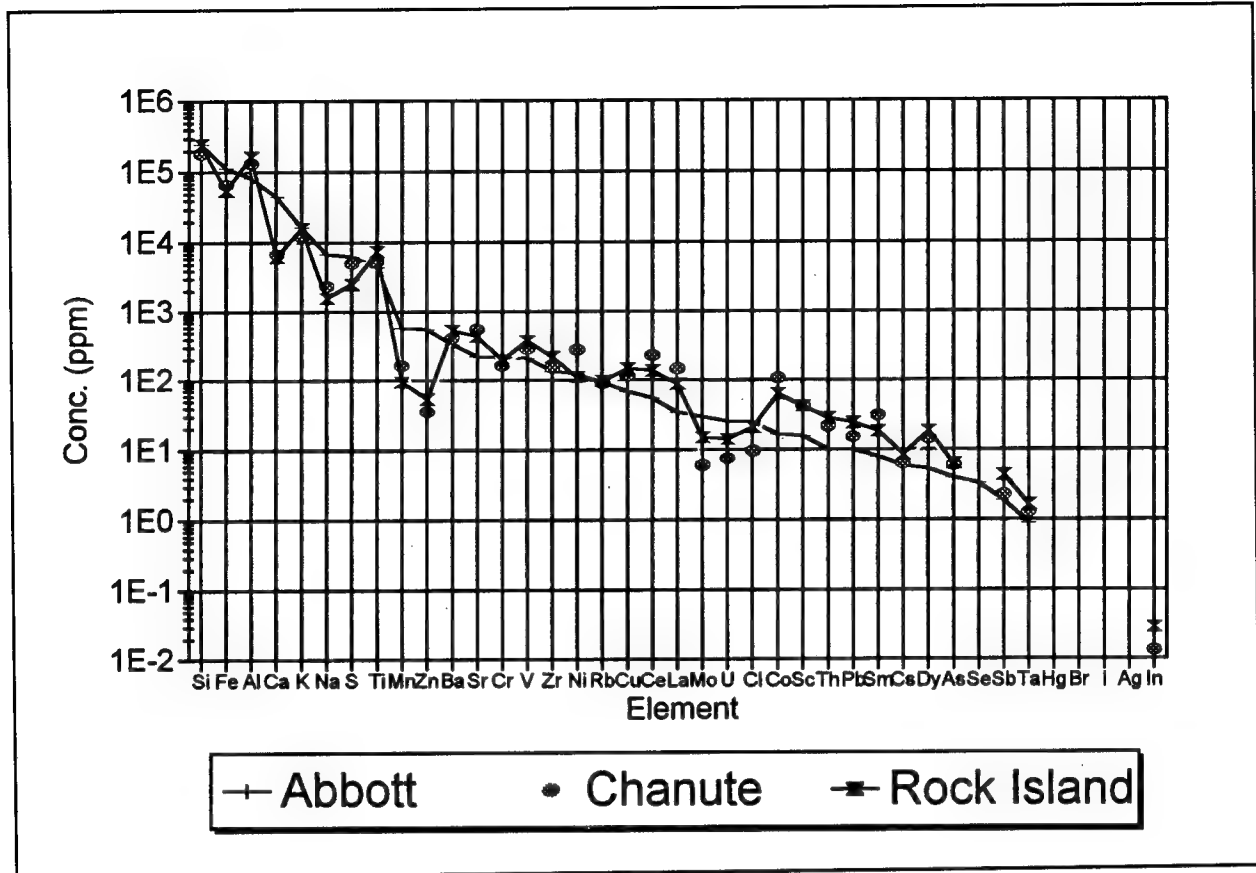


Figure 4. Elemental characterization of bottom ash samples.

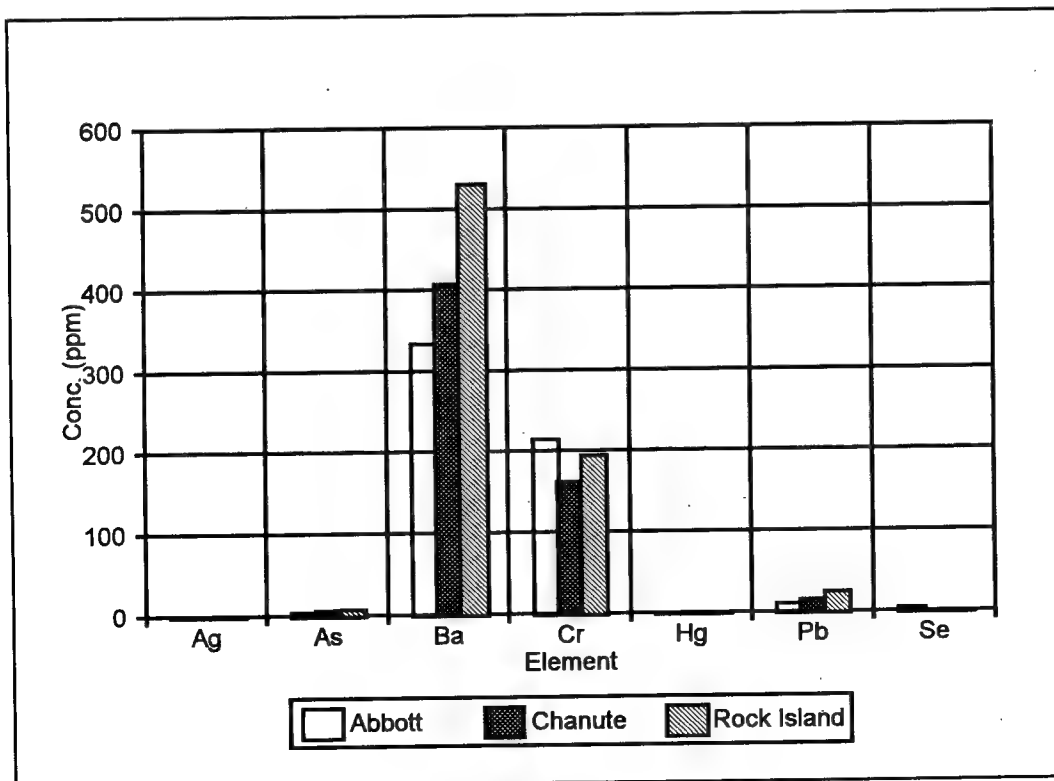


Figure 5. TCLP elements in bottom ash samples.

## Fly Ash

Figure 6 gives an elemental characterization of the fly ash samples. The most abundant elements include Si, Fe, Al, Ca, S, K, and Na. Sulfur levels ranged from 0.6 percent (Rock Island) to 2.3 percent (Abbott). Fly ash sulfur levels were lower compared to the coal levels but higher than the bottom ash levels. Zinc levels (ppm) were substantially higher in the Abbott sample (693 ppm) compared to the Chanute (79 ppm) and Rock Island (44 ppm) ash. (Recall that the Abbott "fly ash" sample was actually a combination of fly and bottom ash.)

Strontium levels in the fly ash ranged from 173 ppm (Abbott) to 470 ppm (Rock Island). These levels were elevated compared to the coal Sr levels. Uranium levels ranged from 6 ppm (Chanute) to 19 ppm (Abbott). Chlorine levels in the fly ash ranged from 28 ppm (Chanute) to 65 ppm (Rock Island).

Figure 7 shows the levels of the TCLP elements in the fly ash samples. Ba and Cr were the most dominant as in the bottom ash. Silver and mercury were not detectable in the samples. Higher levels of As and Pb were found in the fly ash than in the bottom ash.

A comparison of the bottom ash elemental levels to fly ash levels yielded some noteworthy trends. The fly ash samples contained higher levels of As, Cl, Pb, and S

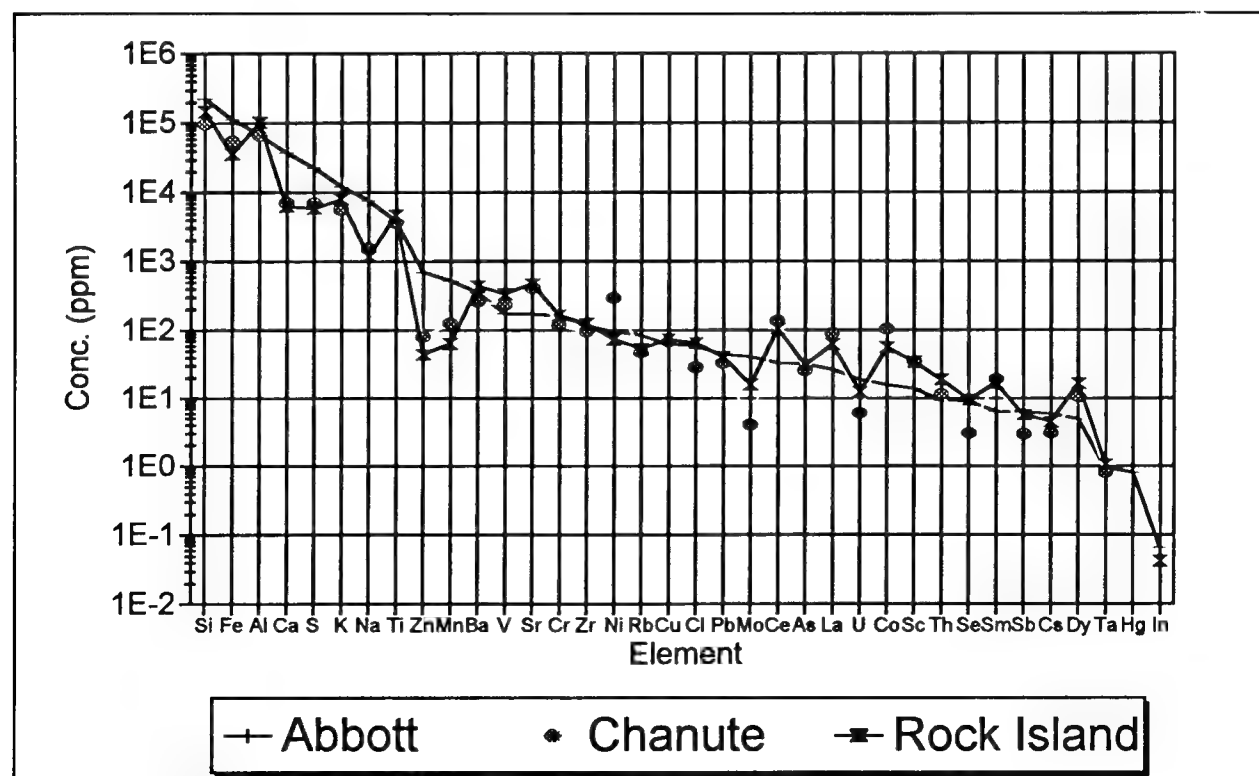


Figure 6. Elemental characterization of fly ash samples.



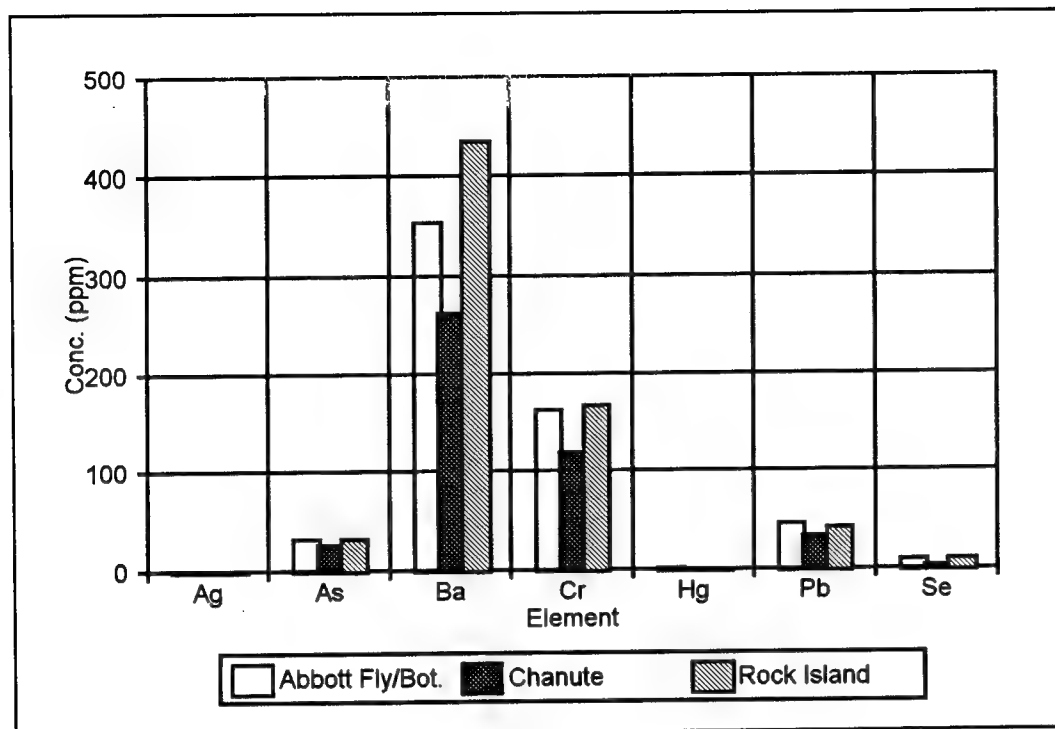


Figure 7. TCLP elements in fly ash samples.

than in the bottom ash samples (all varieties). The Abbott bottom ash and fly ash contained elevated levels of Ca, Fe, Mn, Mo, Na, and Zn compared to the Chanute and Rock Island varieties. Co and Se levels, however, were lower in the Abbott samples. The Chanute samples featured relatively high levels of Ce, Co, La, and Ni.

## Site Data

The TCLP element data are presented in an alternate form in Figures 8, 9, and 10 for the Abbott, Chanute, and Rock Island ash, respectively. Cadmium levels were not determined. The bottom ash samples from the three sites contained more Cr than the fly ash. The dominance of Ba and Cr is again demonstrated.

It should be stressed that the above comparisons between sample varieties should be viewed cautiously. Relative differences between elemental levels in the samples may be used to predict leaching behavior to some extent, but the differences should not suggest a given ash variety is potentially more toxic than another. The reason for examining the differences between the coal and ash from the three sites is to find general trends in the "coal through leachate" pathway. The leaching behavior rather than the presence of contaminants is what is important in determining appropriate disposal and utilization practices.

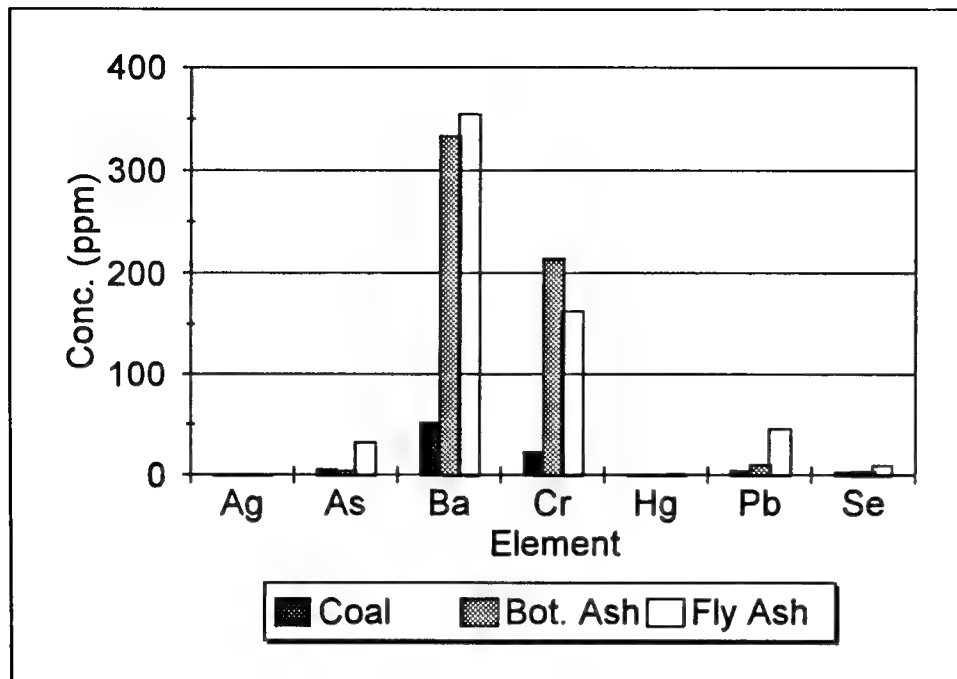


Figure 8. Abbot coal and ash TCLP element data.

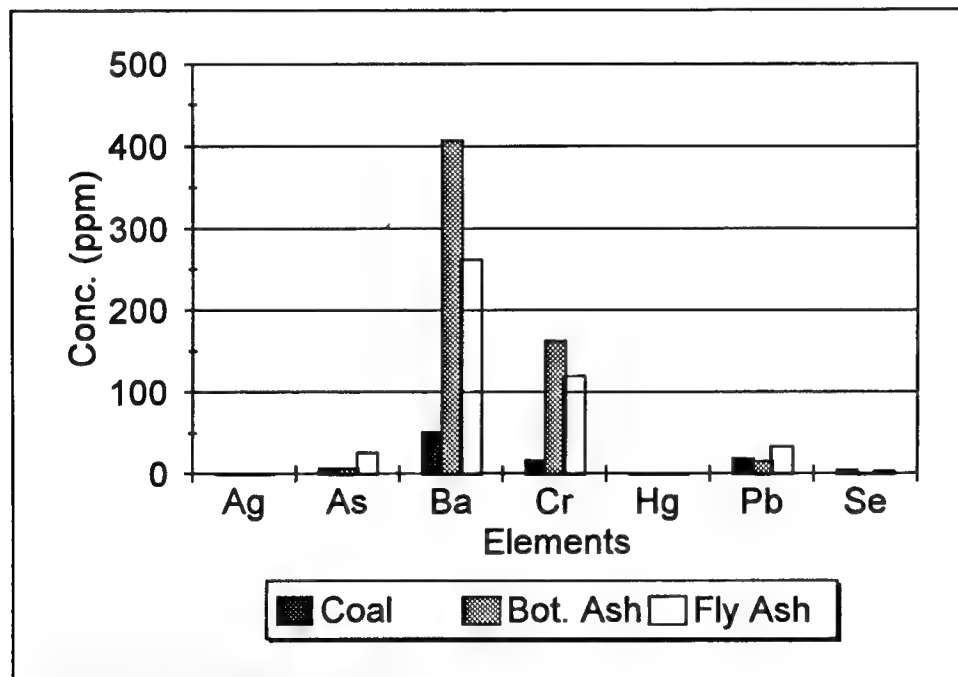


Figure 9. Chanute coal and ash TCLP element data.

## TCLP Results

The bottom ash and fly ash samples from the three sites were subjected to the TCLP leaching test (55 FR 11798-11877). Dilute acetic acid was used as the extracting

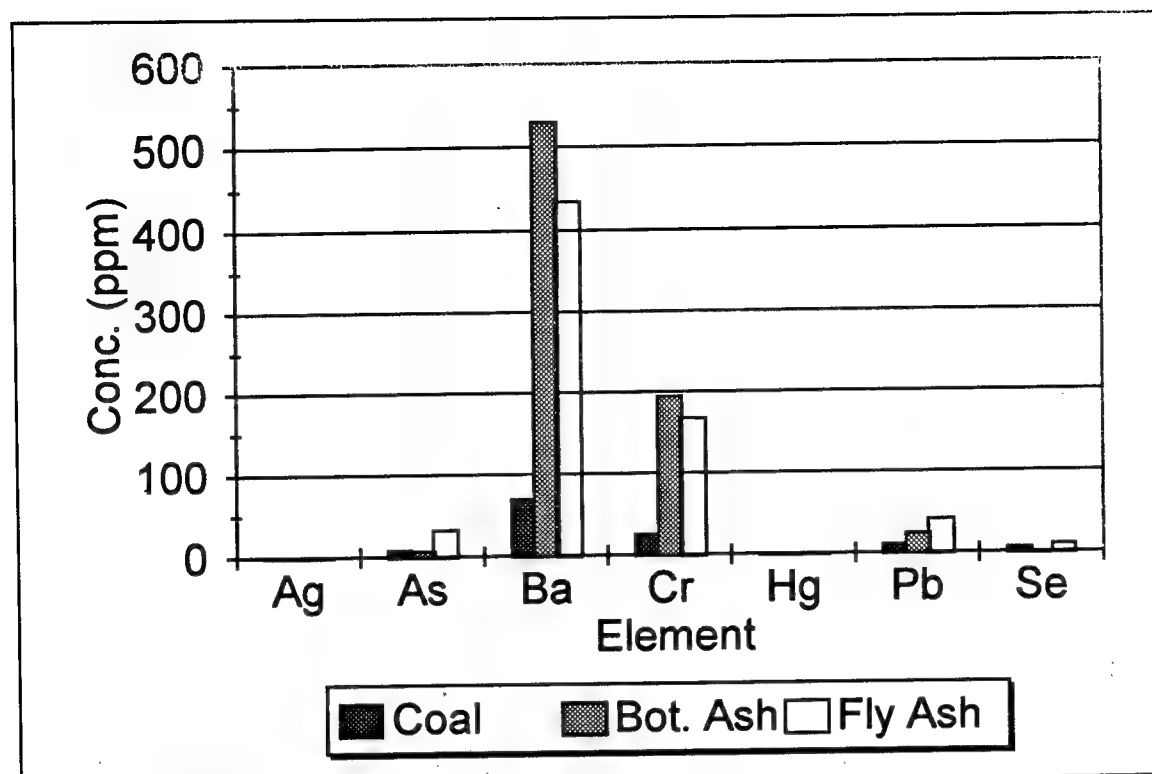


Figure 10. Rock Island coal and ash TCLP element data.

solution. The leachate was filtered and stored in acid-washed polyethylene bottles. The samples were then acidified to  $\text{pH} < 2$ . ICP-AES requires acidification with 2 percent ultra pure  $\text{HNO}_3$  and 5 percent ultra-pure  $\text{HCl}$ . The acidification was performed to keep key elements in soluble forms and to maintain a suitable sample viscosity to pass through the ICP apparatus (Buchholz 1993).

ICP analysis of the extracts yielded levels of TCLP elements well below the statutory limits. Table 6 lists the summary results. Levels of Ag, As, Hg, Pb, and Se were below detection limits in all samples. Minor Ba levels were detected in all leachate samples and cadmium was found only in the Abbott samples. The presence of Ba and Cr in the leachates was somewhat anticipated from the examination of the elemental levels in the ash solids.

Some researchers observed that low silver levels in the extracts may be due to precipitation of  $\text{AgCl}$  following acidification (Buchholz 1993). Since silver is present at low levels in the ash solids (Figures 5 and 7), it is not expected to leach at levels above regulatory limits.

The analytical results strongly suggest the ash solids from the three sites would not be regulated as hazardous waste under the RCRA/TCLP statutes. Coal fly and bottom

Table 6. TCLP results.

Element	Ash Variety	Concentration in Leachate*	Regulatory Level
Ag	All samples below MDL	<0.014 (MDL)	5.0
As	All samples below MDL	<0.23 (MDL)	5.0
Hg	All samples below MDL	<0.062 (MDL)	0.2
Pb	All samples below MDL	<0.072 (MDL)	5.0
Se	All samples below MDL	<0.30 (MDL)	1.0
Ba	Abbott Bottom	0.260	100.0
	Abbott Fly	0.282	
	Chanute Bottom	0.187	
	Chanute Fly	0.213	
	Rock Island Bottom	0.431	
	Rock Island Fly	0.293	
Cd	Abbott Bottom	0.025	1.0
	Abbott Fly	0.200	
	Chanute Bottom	<0.016 (MDL)	
	Chanute Fly	<0.016	
	Rock Island Bottom	<0.016	
	Rock Island Fly	<0.016	
Cr	Abbott Bottom	0.031	5.0
	Abbott Fly	0.050	
	Chanute Bottom	0.022	
	Chanute Fly	<0.020 (MDL)	
	Rock Island Bottom	<0.020	
	Rock Island Fly	0.030	
*All concentrations in mg/L.			

ash wastes are, in fact, currently exempt from Federal hazardous waste regulation. Coal wastes will be assessed under RCRA Subtitle D as nonhazardous waste at the Federal level. Individual states, however, may require the TCLP or other tests to be passed before certain disposal options are allowed.

### Water Batch Extraction

The long-term washing of the bottom ash and fly ash in a monofill environment was simulated using a water-batch extraction technique. The TCLP test is not representative of ash monofill leaching due to its use of acetic acid. Furthermore, the TCLP test fails to address the leaching dynamics of extended washing. Consecutive samples are required to examine not only those elements that leach, but the point in the washing process when these elements are mobilized.

Quality assurance and quality control were maintained through the use of procedure blanks, reagent blanks, deionized water blanks, and appropriate trace metal laboratory procedures, such as by using ultra-pure reagents. Multiple liquid standards were also employed as part of the ICP-AES analysis.

## Procedure

The extraction procedure is outlined in Table 7. A simulated acid-rain solution was prepared by adding low levels of nitric and sulfuric acid to deionized water in a method similar to that used by Buchholz (1993) on municipal solid waste incineration ash.

Typically, the first samples taken from water batch extractions contain the highest concentrations. Since not much can be learned about the initial leaching dynamics from large initial spikes, it is important to begin with low LS ratios to better quantify initial leaching. For this study, the LS ratios were slowly increased, using LS steps of 2 initially, to better characterize the first stages. Samples of leachate from each LS ratio were prepared over consecutive days with agitation periods of approximately 24 hours in between.

Table 8 lists the sampling and corresponding LS ratios used in the extraction. Whatman GF/F glass fiber filters were used for vacuum filtration. After each filtration, the film of ash on the filter was returned to the agitation flask before additional extraction fluid was added. An orbital shaker was used at approximately 200 rpm for agitation of the flasks. Laboratory temperature varied from 20 to 28 °C during the weeks of extraction. All glassware was acid washed, washed with Alconox, rinsed well with deionized water, and rack-dried. Furthermore, all samples were placed in acid-washed polyethylene bottles and acidified appropriately for ICP-AES.

## Results

All liquid samples were analyzed using ICP-AES. Levels of 32 elements were sought in each sample. Many elemental levels, however, were below detection limits in the leachate (water extraction) samples. Appendix D lists concentrations and detection limits.

**Table 7. Water-batch extraction procedure.**

Step	Procedure*
1	Prepare extraction fluid: 1 drop each of $H_2SO_4$ & $HNO_3$ per 30 L carboy to desired pH (4.0-6.0).
2	Measure 200 grams of ash (dry) into 2000 ml flask.
3	Add extraction fluid to ash. Choose liquid-to-solid ratio (LS) as small as possible initially and increase as total LS ratio increases.
4	Place flasks on orbital shaker and agitate for approximately 24 hours. Set speed so that continuous mixing occurs (250 rpm).
5	Remove flasks and allow ash to settle for approximately 30-45 min before filtering.
6	Mount GF/F in vacuum filter holders and wash by filtering 1 L of 1N $HNO_3$ and then rinse with at least 3 L of deionized water.
7	Measure pH of unfiltered extraction fluid by removing 30 ml into a clean beaker and using pH meter.
8	Use large opening serological pipettes to remove clarified fluid from flasks and deliver to filtering flasks.
9	If filter becomes clogged (1-4 mm of ash on it), remove and carefully peel filter away from ash. Place ash pellet on Parafilm, remount filter keeping same side up and continue. Filter until you recover the same amount of fluid added in step 3. A slurry will remain in the bottom of the flask.
10	Add new extraction fluid to ash and restart (at step 4). Remember to replace filtering pellet in slurry flask.
11	Transfer sample of each extraction into plastic sample bottles. Take into account the acid added to acidify the samples. Use a separate pipette for each sample: ICP 2 percent ultra pure grade $HNO_3$ 46.5 ml sample, 1 ml nitric, 2.5 ml hydrochloric; 5 percent ultra pure grade HCl
12	Measure and record pH of filtered fluid.
13	Dispose of remaining fluid in vacuum flask after sample is prepared for each extraction.
14	Clean all glassware for next day's extraction. Acid wash (nitric) for at least 30 min. Then wash with hot soapy water and rinse well with deionized water. Do not use cleansers containing chromium etc.
15	Clean pipettes by drawing acid and rinsing with deionized water.
*Based on extractions performed by Buchholz (1992).	

## pH Considerations

Figure 11 shows the pH change during the water batch extraction of the bottom ash samples. The extracting solution was acidic, but the pH levels of the bottom ash varieties remained alkaline throughout. The buffering capability of the ash would be expected to maintain alkaline leaching conditions in an ash monofill. Furthermore, the pH curves seemed to level off at values well above the leaching solution pH of 6.0. The pH behavior of the bottom ash in this study parallels the results of extractions of municipal solid waste incineration (MSWI) ash performed by Buchholz (1993). According to Buchholz, "Anxiety over the assertions that acid rain can neutralize the alkalinity of the ash in a monofill is grossly exaggerated." The long term behavior of

Table 8. Summary of liquid-to-solid (LS) ratio step size.

Sample No.	LS Step Size	Total LS Ratio
1	2	2
2	2	4
3	2	6
4	2	8
5	2	10
6	4	14
7	4	18
8	4	22
9	4	26
10	4	30
11	4	34
12	4	38
13	4	42
14	4	46
15	4	50

the ash in a monofill is expected to be stable since aggressive (acidic) leaching conditions are not likely to develop.

Figure 12 shows the washing effect on the pH during the fly ash extractions. The pH of the leaching solution was 5.4. The Abbott and Chanute fly ash samples exhibited buffering behavior similar to the bottom ash, but the Rock Island pH was surprisingly acidic. The Abbott and Chanute extraction pH leveled off around 9.0, but the Rock Island levels were between 6.0 and 6.5 in the later stages. Acidity due to contamination from improper glassware cleaning was ruled out by obtaining similar results of measurements made in other flasks with additional samples. The effect

of this acidity, if any, on the Rock Island fly ash leachate concentrations is discussed in **Fly Ash Leaching Samples** (p 41).

### Bottom Ash Leachate Samples

The elements that exhibited the most significant water extraction leaching from the bottom ash include, in descending order, Ca, S, Si, Na, K, Al, Sr, and B. Additionally, lower levels of Mo and V were detected. Two TCLP elements (Ba and Cr) were above detection limits. Table 9 lists the elements at or below detection limits for all LS ratios. The complete data set is tabulated in Appendix D.

Figure 13 shows the leaching pattern for sulfur. The Abbott bottom ash sample leached relatively high levels both initially and throughout the length of the water extraction run. Furthermore, the initial sulfur spike of the Abbott sample was about four times larger than the other varieties, an expected result considering the Abbott variety had higher coal and bottom ash sulfur concentrations.

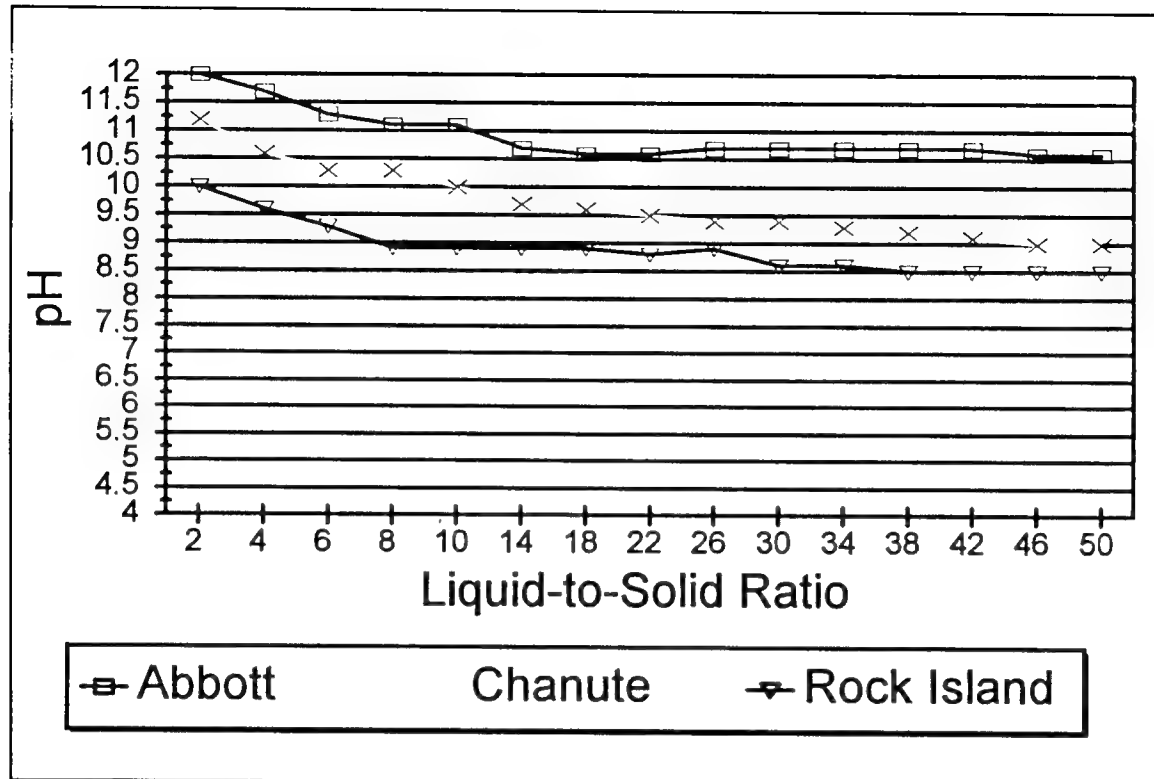


Figure 11. Washing effect on pH during water batch extractions of bottom ash.

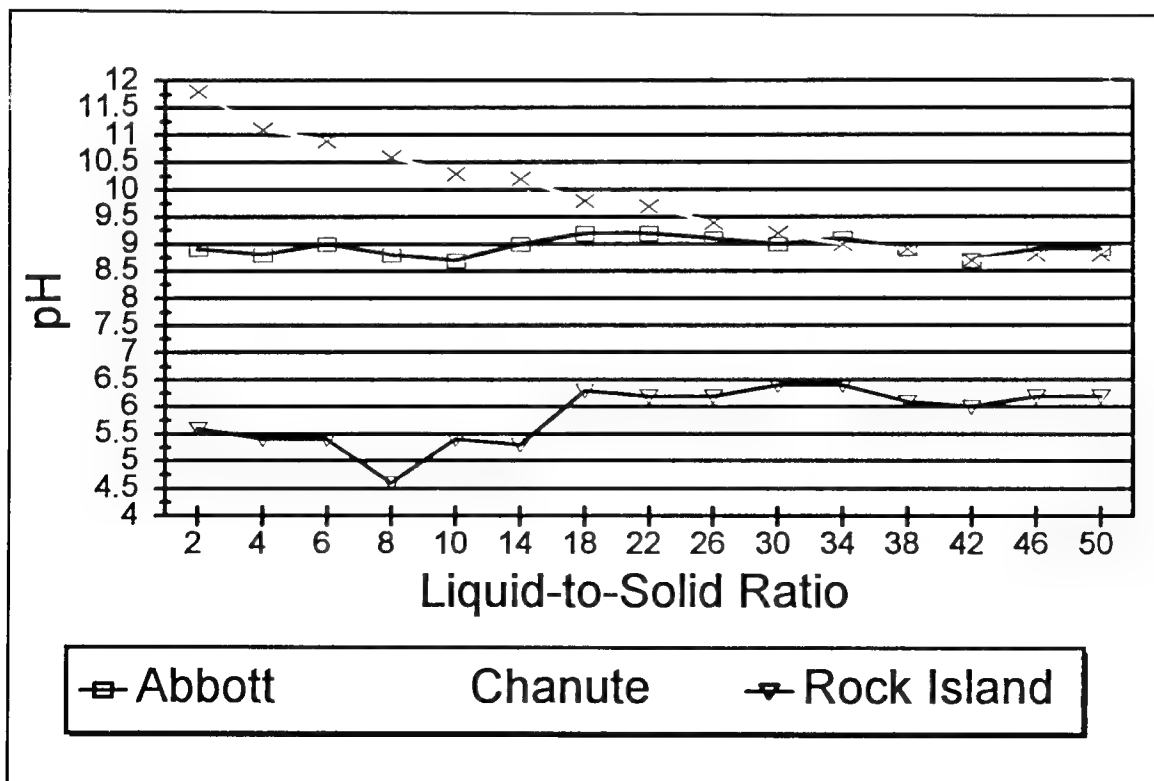


Figure 12. Washing effect on pH during water batch extractions of fly ash.



Table 9. Bottom ash elements at or below detection limits for all liquid-to-solid ratios (2-50).

Element	Detection Limit	Unit
Ag	<0.014	mg/L
As	<0.183	mg/L
Be	<0.003	mg/L
Cd	<0.014	mg/L
Co	<0.021	mg/L
Cu	<0.009	mg/L
Hg	<0.066	mg/L
Mn	<0.004	mg/L
Ni	<0.040	mg/L
P	<0.412	mg/L
Pb	<0.088	mg/L
Sb	<0.500	mg/L
Se	<0.250	mg/L
Sn	<0.110	mg/L
Ti	<0.004	mg/L
Tl	<0.340	mg/L

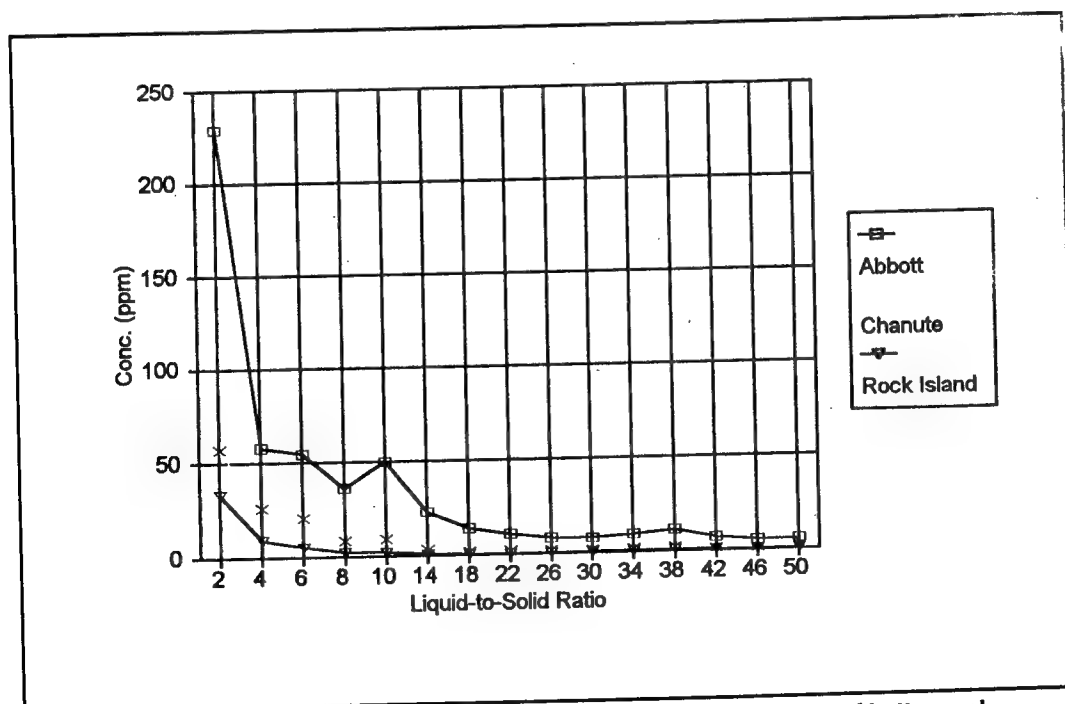


Figure 13. Leaching pattern for sulphur in water batch extraction samples of bottom ash (MDL = 0.240 ppm).

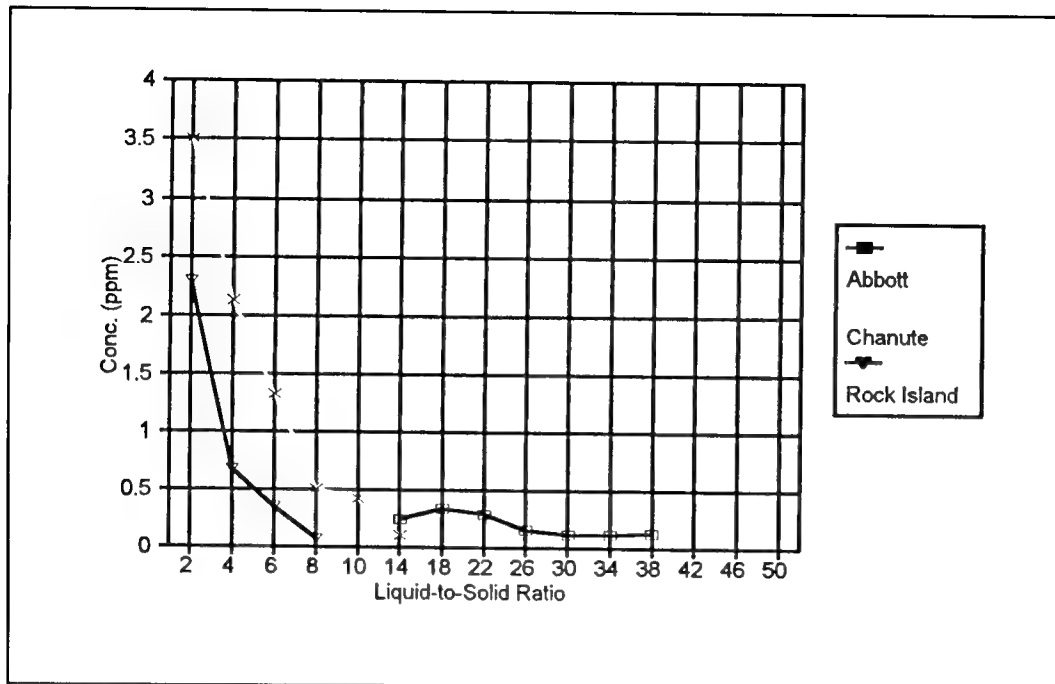


Figure 14. Leaching pattern for boron in water batch extraction samples of bottom ash. (MDL = 0.039 ppm)

Figure 14 shows the leaching pattern for boron. The highest levels of B were leached from the Chanute bottom ash sample, which featured an initial spike of 3.5 ppm. The Abbott bottom ash sample did not leach detectable levels of B until the middle of the run. The shape of the Chanute and Rock Island patterns is typical for elements susceptible to quick initial leaching with falling levels thereafter.

Figure 15 shows the strontium leaching pattern. The Abbott bottom ash leached the highest strontium levels and showed an initial spike of about 3.4 ppm, an unexpected result as Abbott bottom ash contained the lowest Sr levels of the three sites. In all three ash types, levels of Sr in leachate samples dropped off as run length increased.

Figure 16 shows the leaching pattern for Mo. Mo was present at detectable levels only in the initial extract samples. The Rock Island and Abbott bottom ash leached more Mo than the Chanute ash. The Chanute bottom ash solids did, in fact, contain lower levels of Mo than the other varieties.

Figure 17 shows the leaching pattern for vanadium. The Rock Island bottom ash had the highest amount of vanadium leaching, Chanute second, and Abbott last. The Abbott bottom ash showed slightly delayed leaching and slightly increasing vanadium levels in the middle extracts but the levels in question were too low to be significant.

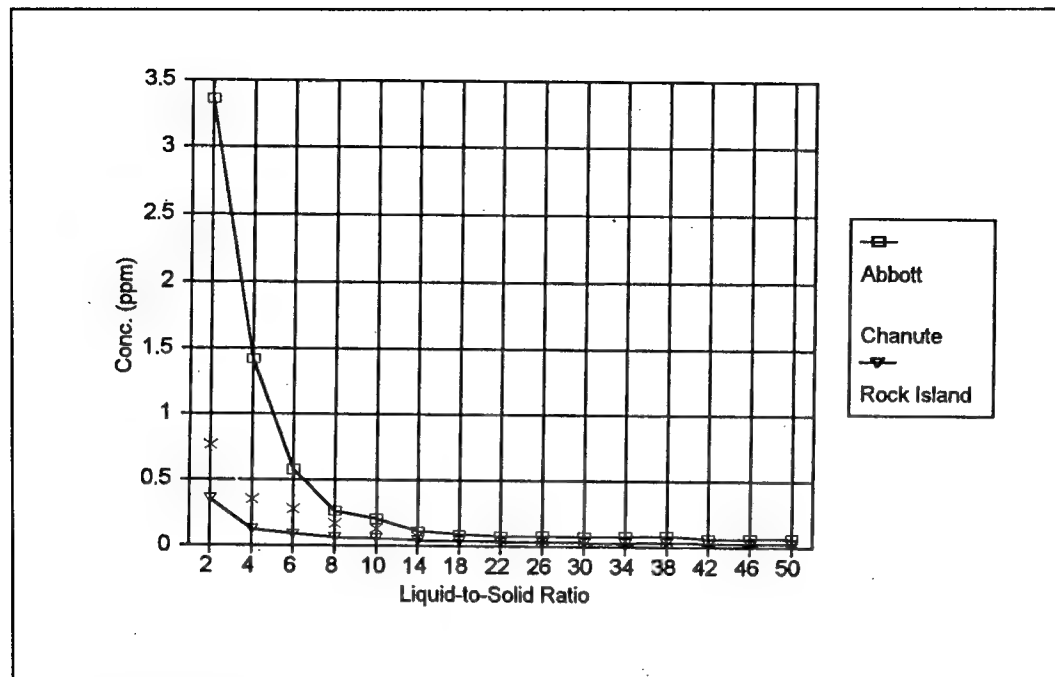


Figure 15. Leaching pattern for strontium in water batch extraction samples of bottom ash (MDL = 0.002 ppm).

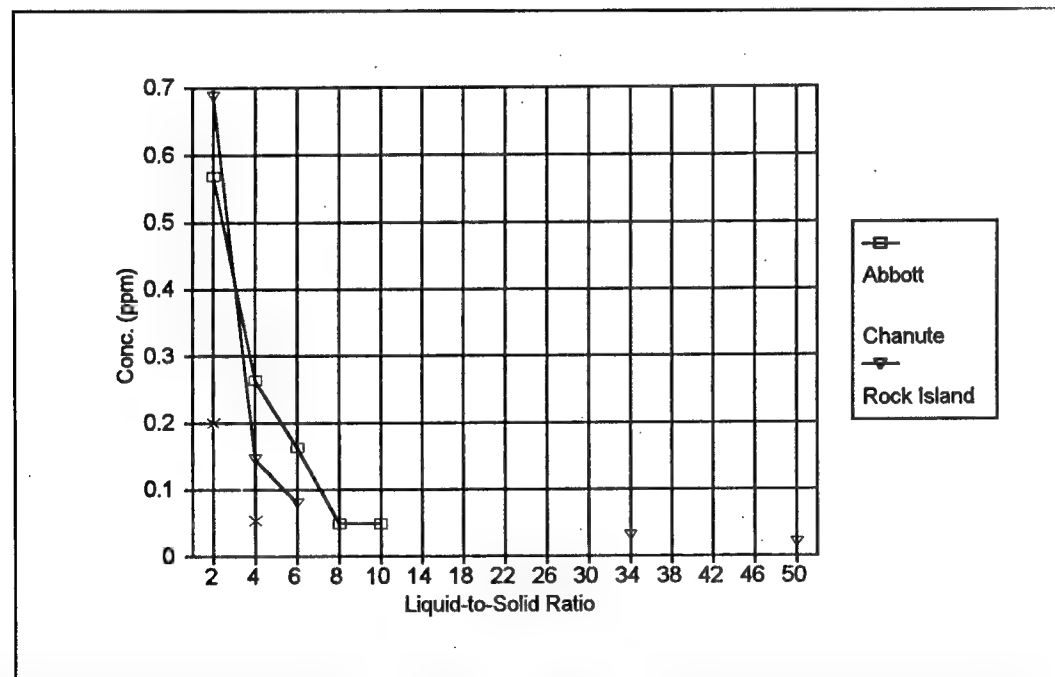


Figure 16. Leaching pattern for molybdenum in water batch extraction samples of bottom ash (MDL = 0.016 ppm).

Levels in the bottom ash extracts of all of the TCLP elements, except Ba and Cr, were below detection limits. Figure 18 shows the leaching pattern for Ba. The levels of Ba in the extracted bottom ash samples were quite low. The largest concentration spike

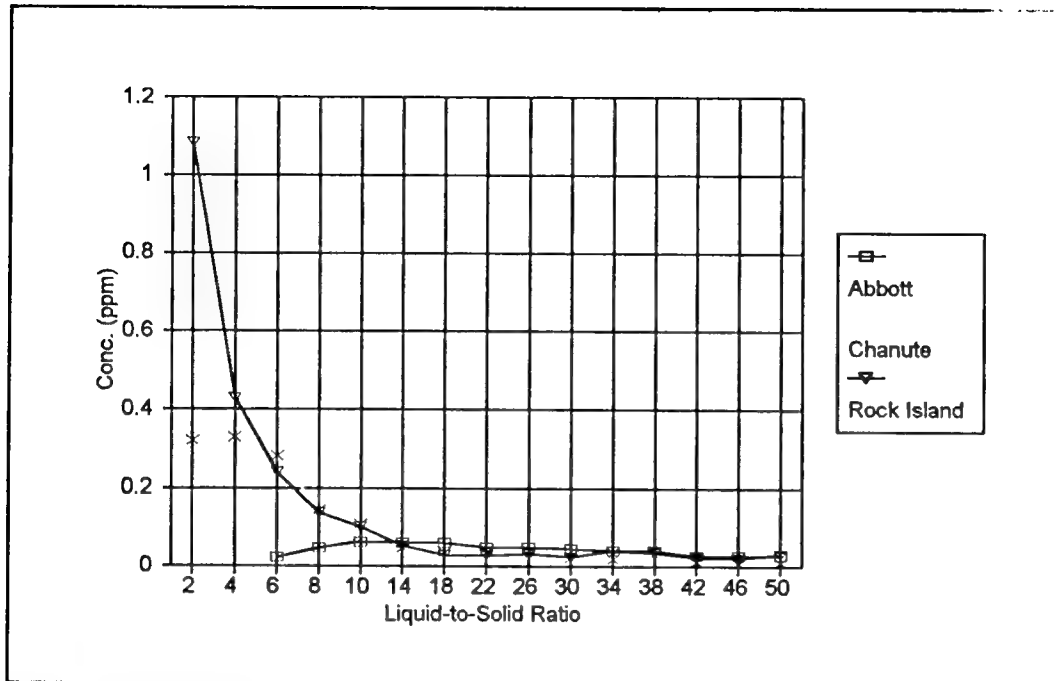


Figure 17. Leaching pattern for vanadium in water batch extraction samples of bottom ash (MDL = 0.009 ppm).

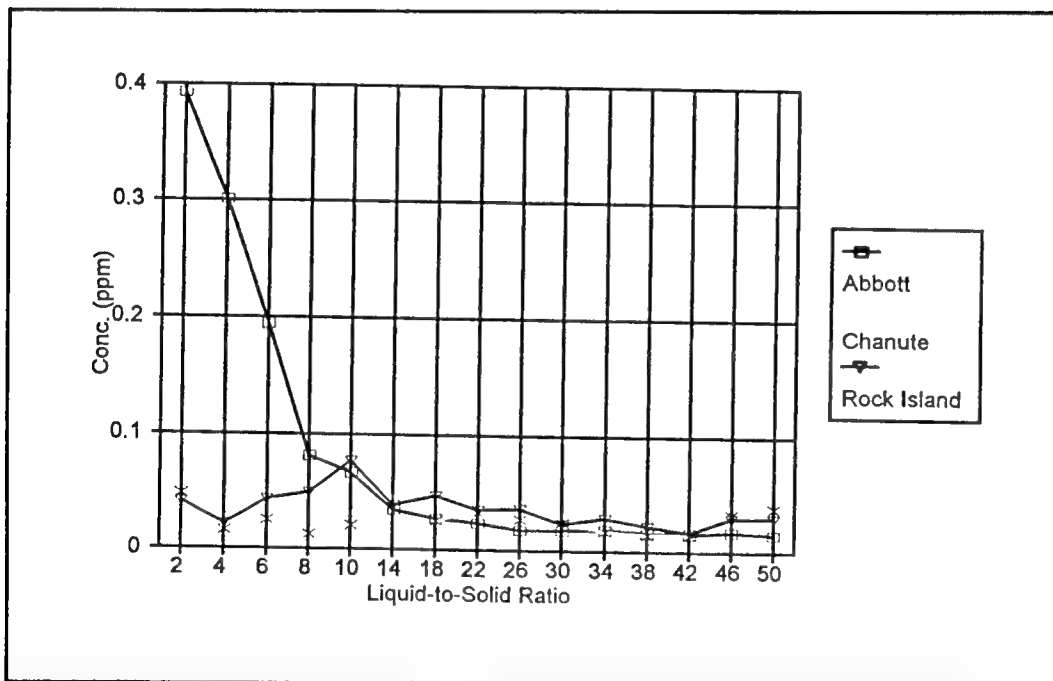


Figure 18. Leaching pattern for barium in water batch extraction samples of bottom ash (MDL = 0.009 ppm).

belonged to the Abbott bottom ash sample (0.4 ppm). Ba levels in the Chanute and Rock Island bottom ash samples did not exceed 0.1 ppm for the duration of the run.

Figure 19 shows the leaching pattern for Cr in the bottom ash. The Cr levels were very minor and undetectable in most extract samples. The bottom ash elements that

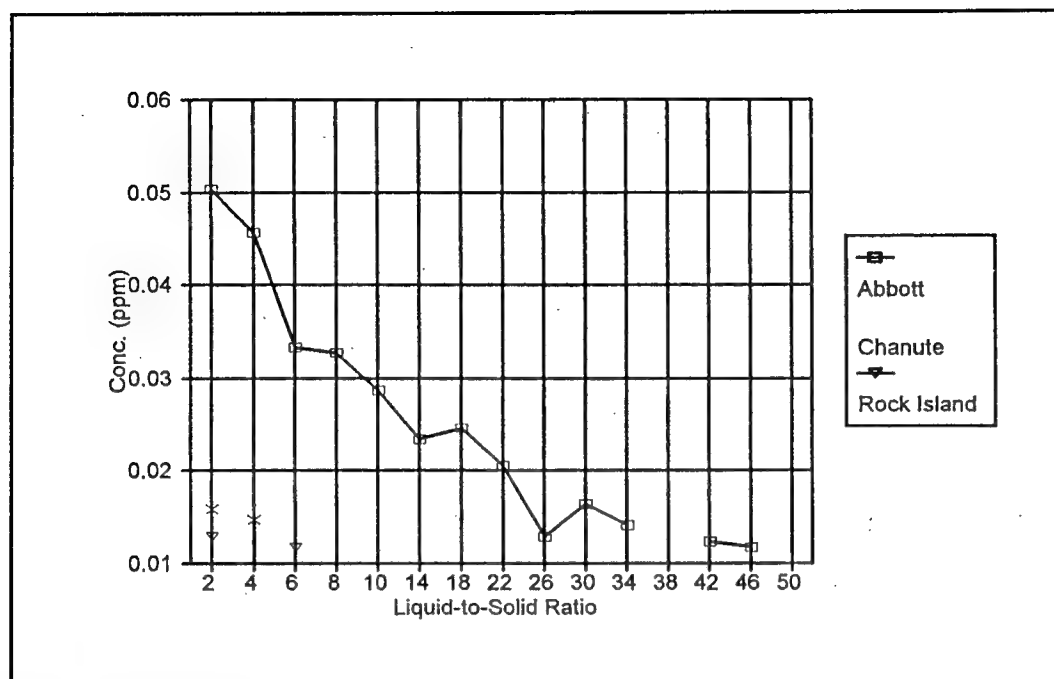


Figure 19. Leaching pattern for chromium in water batch extraction samples of bottom ash (MDL = 0.011 ppm).

were susceptible to quick initial leaching are Al, B, Ca, K, Mo, Na, S, Si, and Sr. Some elements showed increasing levels as the water extractions progressed. For example, silicon levels in the Abbott leachate increased with the LS ratio. The internal silicate matrices of the ash particles in the Abbott bottom ash sample were apparently more prone to leaching solution attack than the matrices of the Chanute and Rock Island varieties. Furthermore, aluminum (Abbott and Rock Island) and magnesium (Abbott and Chanute) levels increased during the middle stages of bottom ash leaching.

Figure 20 shows elemental leachate totals of all LS ratio samples added together for the bottom ash. The Abbott bottom ash leached higher levels of Ca, S, Si, Na, K, Al, and Sr. The Chanute ash leached relatively high levels of boron. Of environmentally important elements, S, Sr, B, and V may be of concern. Levels of the TCLP elements Ba and Cr in the leachates were minor and the mobility of Mo was apparently low.

### Fly Ash Leachate Samples

The elements that exhibited the most significant leaching from the fly ash were, in descending order, S, Ca, Na, K, B, Si, Mg, Al, and Sr. Table 10 lists the elements at or below detection limits for all LS ratios. Appendix D lists comprehensive data. Figure 21 lists the fly ash leaching pattern for sulfur. As with the bottom ash, the Abbott fly ash leached the highest amounts. The Abbott fly ash sample continued to leach relatively higher levels compared to the Chanute and Rock Island samples until

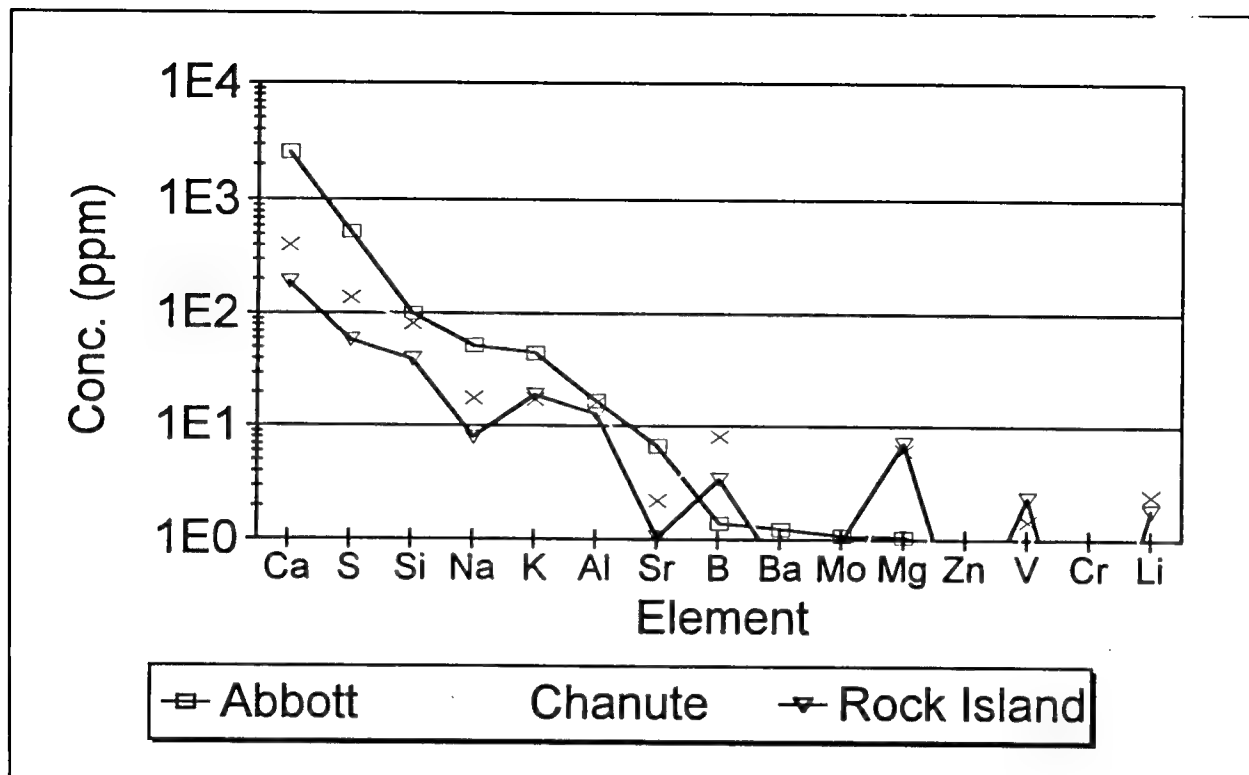


Figure 20. Leachate totals in bottom ash extracts.

Table 10. Fly ash elements at or below detection limits for all liquid-to-solid ratios (2-50).

Element	Detection Limit	Unit
Ag	<0.008	ppm
As	<0.280	ppm
Be	<0.002	ppm
Cd	<0.024	ppm
Co	<0.009	ppm
Cr	<0.018	ppm
Cu	<0.006	ppm
Fe	<0.003	ppm
Hg	<0.040	ppm
Pb	<0.051	ppm
Sb	<0.270	ppm
Se	<0.490	ppm
Sn	<0.041	ppm
Ti	<0.003	ppm
Tl	<0.350	ppm

LS ratios reached 30 or so. By the end of the extraction run (LS 50), all samples leached S at much lower than initial levels. Sulfur levels in the Abbott and Chanute fly ash leachates never dropped below 3 ppm during the extractions (to LS ratio 50). A comparison of Figures 21 and 13 reveals that the fly ash leached sulfur at significantly higher levels than the bottom ash.

Figure 22 shows the leaching pattern for boron. The three fly ash types exhibited similar behavior, relatively high initial leaching with falling levels thereafter. Levels of boron in the fly ash leachates were higher than in the bottom ash leachates. Figure 23 shows the fly ash leaching pattern for strontium. The Rock Island fly ash leached the highest levels and featured an initial spike of about 9 ppm. The lower pH of

the early Rock Island extracts (cf. Figure 12) may have been a factor causing this spike. Falling levels throughout the length of the run were again characteristic of all three varieties.

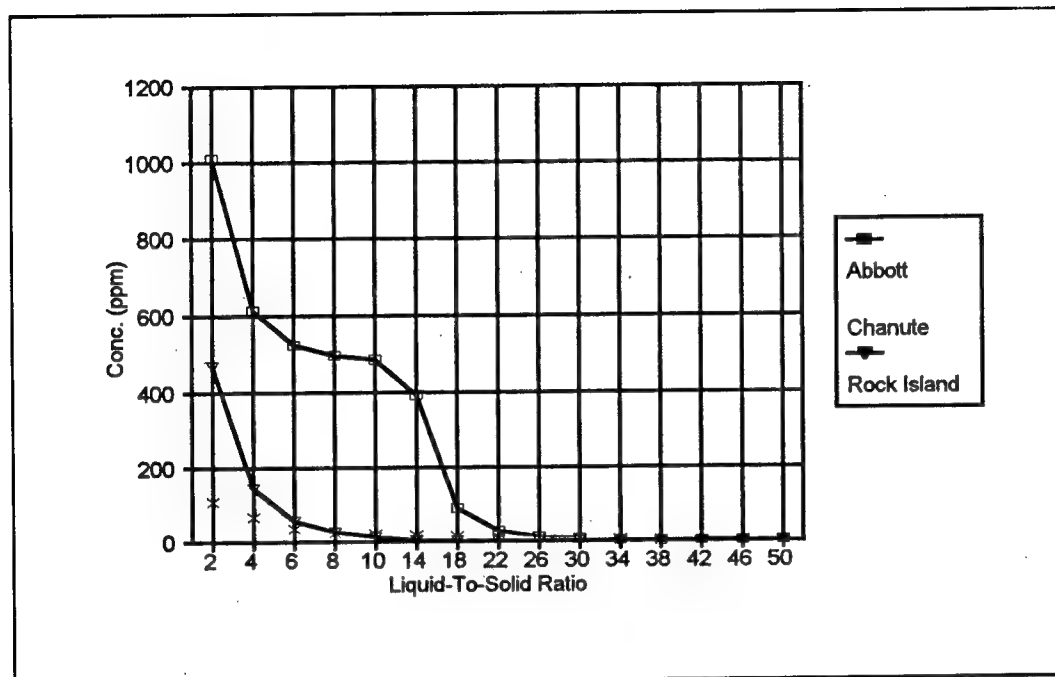


Figure 21. Leaching pattern for sulphur in water batch extraction samples of fly ash (MDL = 0.09 ppm).

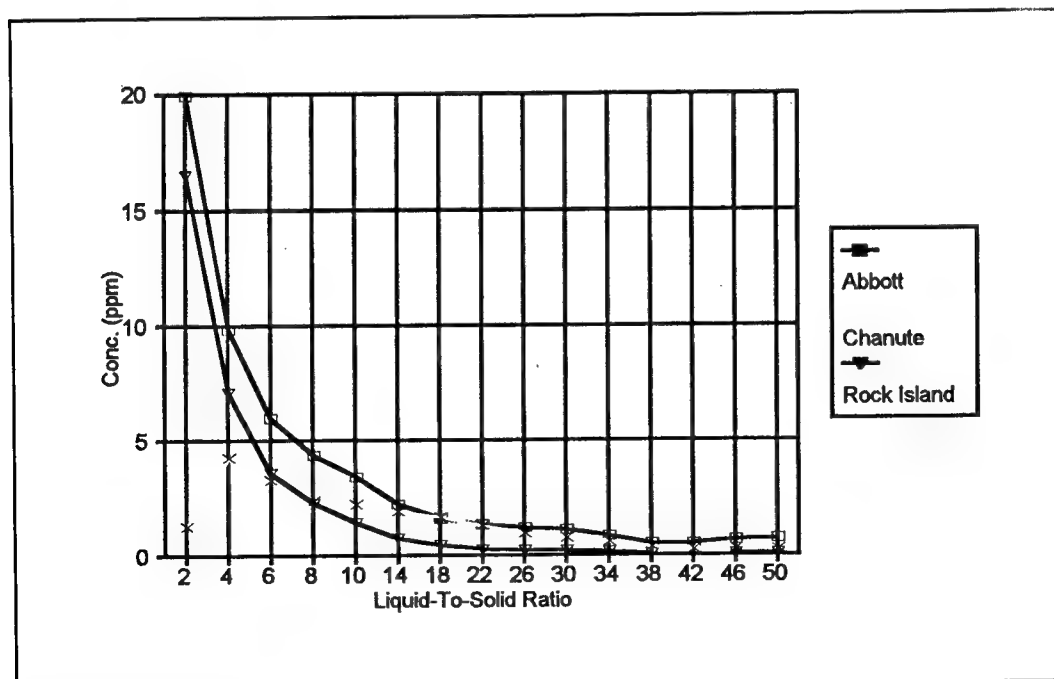


Figure 22. Leaching pattern for boron in water batch extraction samples of fly ash (MDL = 0.03 ppm).

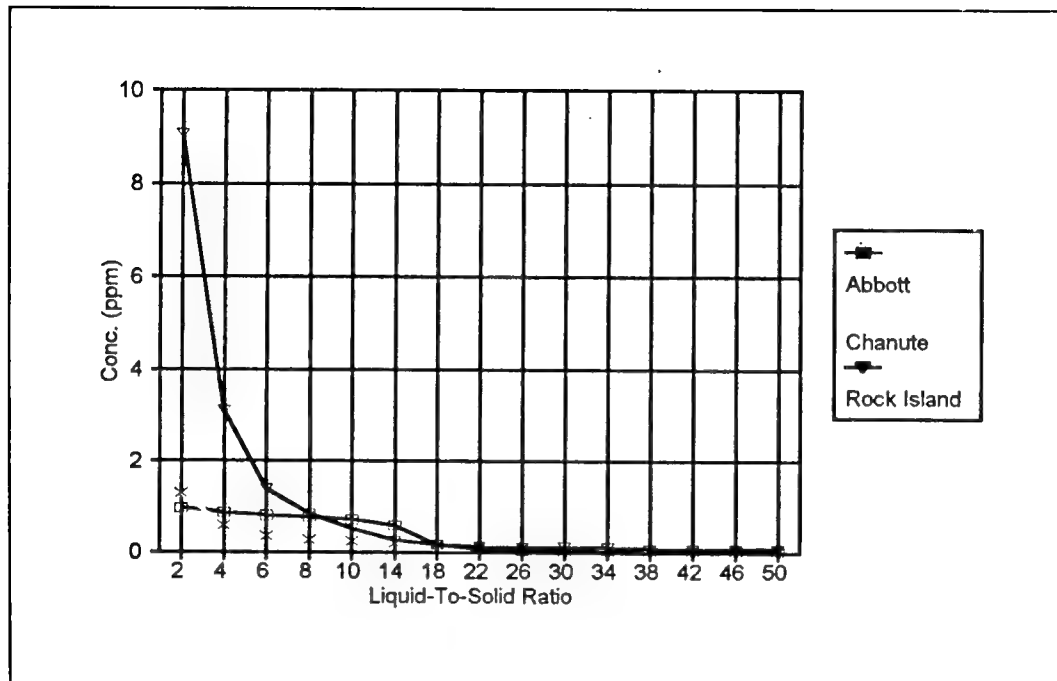


Figure 23. Leaching pattern for strontium in water batch extraction samples of fly ash (MDL = 0.003 ppm).

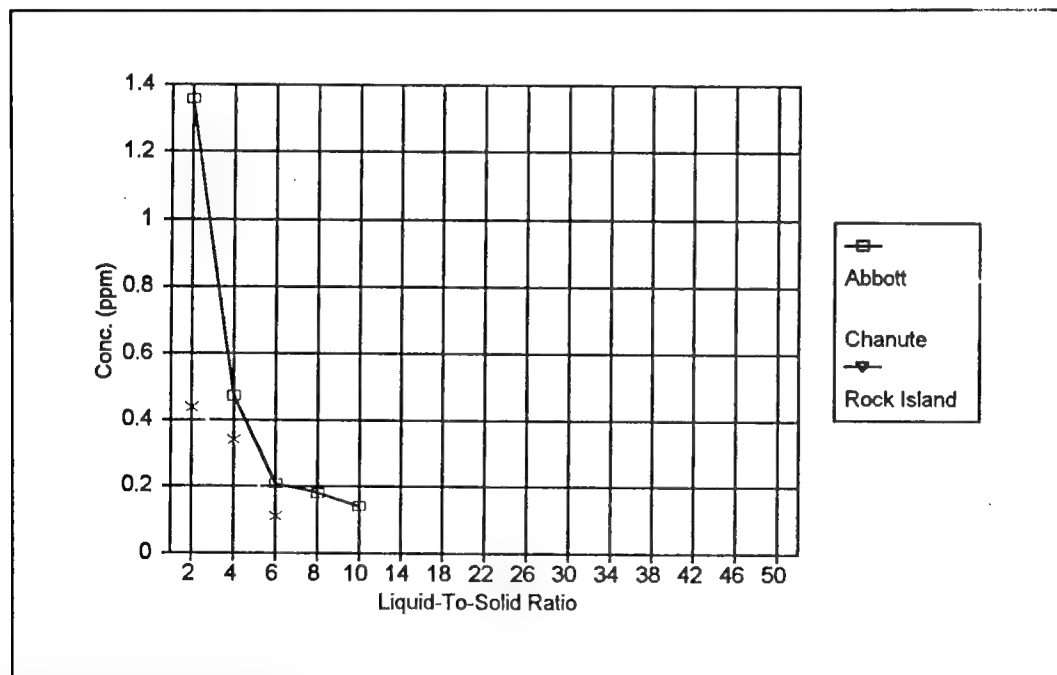


Figure 24. Leaching pattern for molybdenum in water batch extraction samples of fly ash (MDL = 0.09 ppm).

Figure 24 shows the fly ash leaching pattern for molybdenum. Only the Abbott and Rock Island fly ash varieties leached detectable amounts of Mo. Significant Mo did not leach in any of the fly ash extract samples after LS ratio 10.



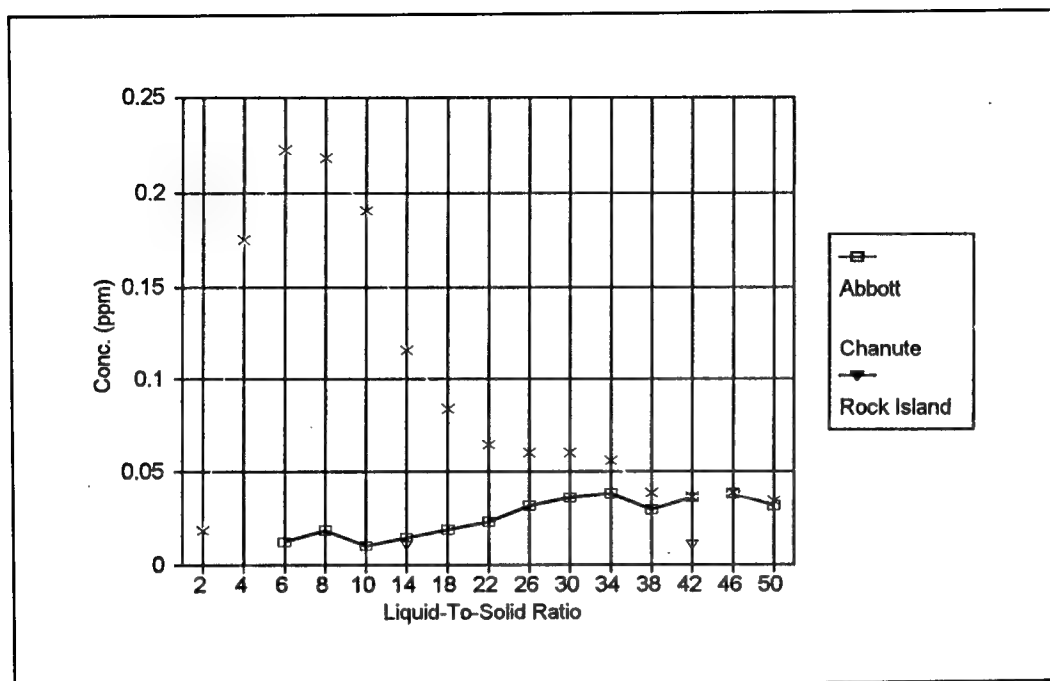


Figure 25. Leaching pattern for vanadium in water batch extraction samples of fly ash (MDL = 0.009 ppm).

Figure 25 shows the leaching pattern for vanadium in the fly ash. The Chanute fly ash leached the highest levels of the three types and did not peak until LS ratio 6. The Abbott fly ash exhibited increasing V mobility, but the concentrations in question are quite low. Leaching of V in the Rock Island fly ash was negligible.

The TCLP elements, except for Ba, were below detection limits in the fly ash extracts for all LS ratios. Figure 26 shows the fly ash leaching pattern for barium. Though detectable, the Ba levels were minor. This may indicate that the Ba in the fly ash is remaining in an insoluble form such as barite ( $\text{BaSO}_4$ ). The Abbott fly ash curve shows increasing Ba levels after first reaching a minimum level. This may be explained by the outer layers of the fly ash matrices having been washed off, thereby exposing more barium to the leaching solution.

Certain elements not found in the bottom ash leachate samples were detected at minor levels in the fly ash leachate samples. For example, the Rock Island fly ash leached low levels of Ni and Co in the first few extracts. Both the Chanute and Rock Island fly ash varieties leached small amounts of phosphorus. Some elements showed increasing levels as the extractions progressed. For example, silicon and aluminum levels in the Abbott fly ash leachate increased with the LS ratio. The Abbott fly ash was apparently most susceptible to such internal matrix attack.

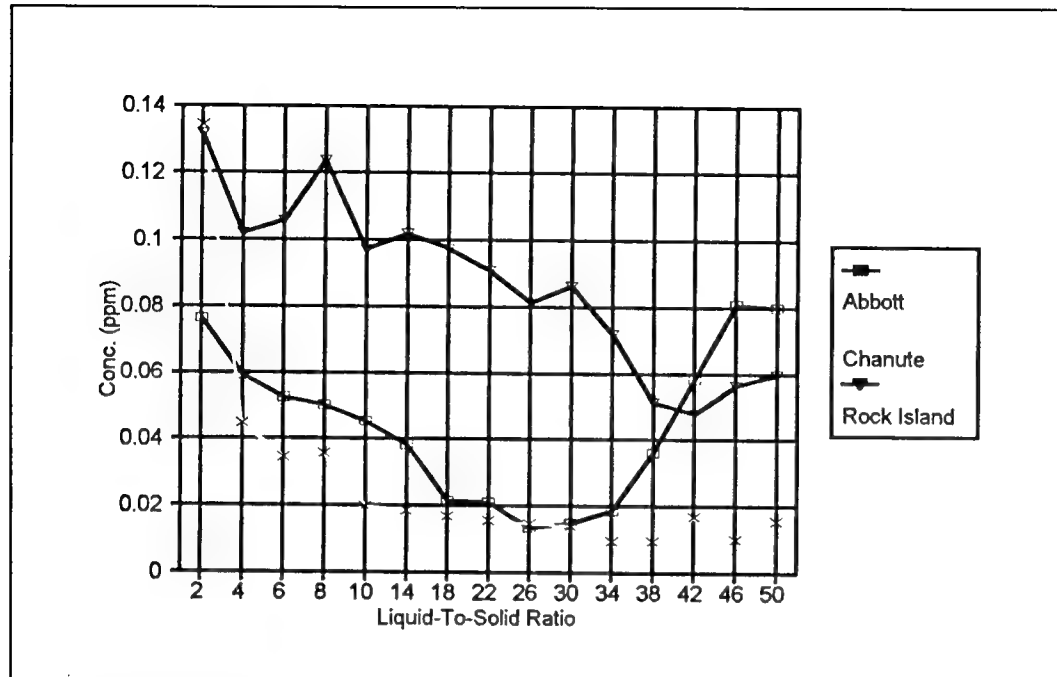


Figure 26. Leaching pattern for barium in water batch extraction samples of fly ash (MDL = 0.002 ppm).

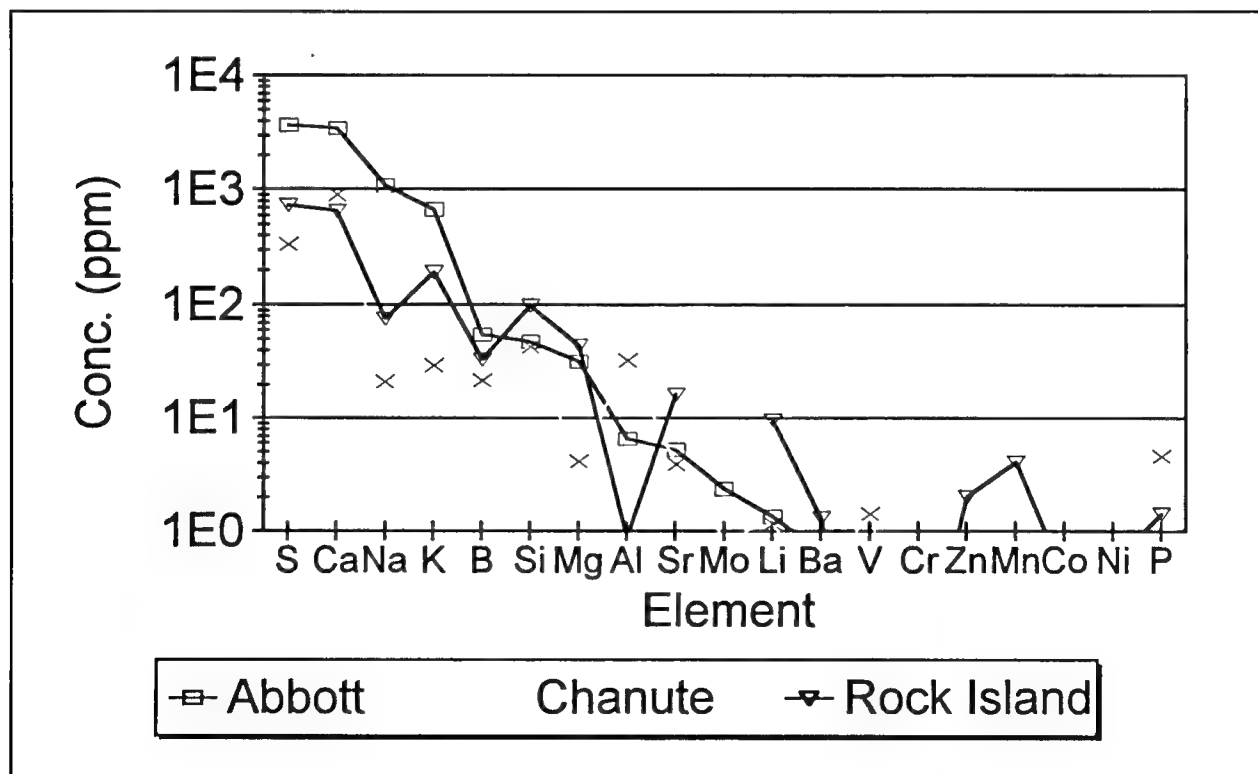


Figure 27. Leachate totals in fly ash extracts.

Figure 27 shows elemental leachate totals of all LS ratio sample levels added together for the fly ash. The Abbott fly ash leached higher levels of S, Ca, Na, K, and B. The

Rock Island fly ash leached the most Sr. The results indicate that out of the environmentally important elements, S, Sr, and B may be of concern. The very minor levels of the two detectable TCLP elements, Ba and Cr, in the leachates are evident. Furthermore, the relatively low mobility of both Mo and V is demonstrated.

### Characterization of Residual Solids

Neutron activation analysis (NAA) was performed on the residual ash from the water batch extractions. The following elements were analyzed: Al, Ca, Na, Ti, Mn and V. Table 11 lists initial (before the water batch extraction) and residual (washed, post-extraction ash) concentrations as well as estimated percent leached figures. The uncertainties associated with the initial ash concentrations are listed in Appendix D. Concentration values reported for the residual ash can be assumed to have errors within 5 to 10 percent.

Note that the Abbott fly ash sample (AF) was a combined fly and bottom ash sample. As expected, the fly ash samples tended to leach higher amounts of the above elements, most likely due to the higher initial concentrations in the fly ash. Bottom ash from the Abbott site leached relatively lower levels than the other ash varieties. Cal-

Table 11. Comparison of initial and residual ash concentrations (ppm).

Element	Initial	Residual	Estimated % leached
<b>AB</b>			
Al	83000	66468	20.0
Ca	45000	40000	11.1
Na	6800	6100	10.3
Ti	4410	3590	18.6
Mn	573	485	15.3
V	211	172	18.5
<b>CB</b>			
Al	132000	95070	28.0
Ca	6700	4000	40.3
Na	2340	1810	22.6
Ti	5350	4200	21.5
Mn	162	109	32.7
V	284	197	30.6
<b>RB</b>			
Al	164000	129284	21.2
Ca	6200	4500	27.4
Na	1570	1250	20.4
Ti	7510	5700	24.1
Mn	95	61	35.8
V	374	256	31.6
<b>AF</b>			
Al	69000	61463	10.9
Ca	38000	27800	26.8
Na	7600	5800	23.7
Ti	3970	3520	11.3
Mn	521	439	15.7
V	178	159	10.7
<b>CF</b>			
Al	67000	48918	27.0
Ca	7100	3700	47.9
Na	1570	970	38.2
Ti	3590	2300	35.9
Mn	127	82	35.4
V	232	139	40.1
<b>RF</b>			
Al	103000	78340	23.9
Ca	6300	3100	50.8
Na	1170	850	27.4
Ti	4680	3460	26.1
Mn	64	37	42.2
V	340	255	25.0
<b>Codes:</b>			
AB	Abbott bottom ash		
CB	Chanute bottom ash		
RB	Rock Island bottom ash		
AF	Abbott fly/bottom ash		
CF	Chanute fly ash		
RF	Rock Island fly ash		

cium and magnesium featured the highest estimated total percentage leached. Aluminum, however, clearly leached the highest concentration levels. Due to losses associated with the water batch leaching technique, strict mass balances could not be readily performed. The water batch method, however, is an effective tool for comparing the leaching behavior of multiple samples and the relative mobilities of elements within individual samples.

## Sequential Extraction

The water batch extraction provides the researcher with information on the leaching dynamics of metals in alkaline environments. In another testing approach involving the use of selective reagents in a sequential manner, certain fractions of the ash can be examined. Sequential extractions of this type offer qualitative insight into the chemical speciation of leachate constituents.

This study applied a modified version of a sequential extraction developed by Tessier et al. (1979) to the ash varieties. The technique was originally used to analyze riverbed sediments, but is suitable for soil and ash samples as well. Wadge and Hutton (1987) performed sequential extractions on coal ash to obtain data on chemical associations of Cd and Pb.

Researchers must use caution in discussing the significance of results obtained from sequential extractions, as exact chemical speciation is unattainable. At each step in a sequential procedure, specific reagents are added to the sample and the resulting extract is analyzed for elemental concentrations. The extracted elements are assumed to have been speciated into a chemical form associated with the reagent. For example, elements extracted with a 1 Mol  $\text{MgCl}_2$  reagent are assumed to be associated with a chemical form including readily exchangeable ions. Many types of complex ions are involved in leaching, however, and no single reagent is specific to only one chemical form. Further limitations include readsorption, precipitation, and losses on centrifuge tube walls. Relative differences and trends, however, in the leaching behavior of ash types can be examined. For example, the first extraction in the sequence is designed to leach readily exchangeable metals by introducing excess cations. Subjecting multiple samples to similar leaching environments in succession should allow for comparisons between not only ash varieties, but a few operationally defined fractions.

## Procedure

The bottom and fly ash samples needed no further preparation. All extractions took place in acid-washed 50 ml polypropylene centrifuge tubes. Table 12 outlines the procedure. The chemical forms (also listed in Table 12) are readily exchangeable, bound to carbonates and surface oxides, bound to iron/manganese oxides, bound to organic matter/sulfides, and residual (remaining ash) (Tessier et al. 1979).

The centrifuge tubes were centrifuged at 10000 rpm for 30 minutes following each extraction. The supernatant was then carefully removed with a Pasteur pipette and placed in acid-washed polyethylene sample bottles. Next, 8 ml of deionized water was added to the tubes to wash the remaining residue. The washing solution was then spun at 10000 rpm for 30 minutes and the resulting supernatant discarded prior to the next extraction step.

As with the water batch extractions, quality control was maintained through the use of high grade reagents, procedure blanks, and deionized water blanks. Leachate samples were acidified appropriately for ICP analysis with ultra-pure acid.

## Analysis

Liquid samples of the various extractions were analyzed by ICP-AES. Due to the nature of the extractions and the chemical composition of the reagents, some elemental levels exceeded calibration ranges or overloaded the detection electronics of the ICP

**Table 12. Sequential extraction procedure proposed to determine chemical forms.**

Step	Chemical Fraction	Extraction Technique	Procedure
1	Readily exchangeable ions	Exchange with excess cations	1M MgCl <sub>2</sub> (8 ml), pH 7.0 1 h at room temperature, continuous agitation.
2	Carbonate bound, surface oxide bound ions	Release by mild acid	1M NaOAc adjusted to pH 5.0 with HOAc (8ml), 5 h at room temperature, continuous agitation.
3	Ions bound to Fe-Mn oxides	Reduction	0.04M NH <sub>2</sub> OH HCl in 25 percent (v/v) HOAc (20 ml), 6 h at 96 ± 3 °C, occasional agitation.
4	Organically and sulfide bound ions	Oxidation	0.02M HNO <sub>3</sub> (3 ml) + 30 percent H <sub>2</sub> O <sub>2</sub> (5 ml) adjusted to pH 2.0 with HNO <sub>3</sub> , 2 h at 85 ± 2 °C, occasional agitation. After cooling to room temperature, 3.2M NH <sub>4</sub> OAc in 20 percent (v/v) HNO <sub>3</sub> (5 ml), 0.5 h, continuous agitation.
5	Residual	None	Dry at 65 °C for 72 h.
*Based on 1.0 g sample extractions by Tessier et al. (1979).			

apparatus. Ca and Na levels in the exchangeable fraction fall into this category. Sample dilution by a factor of eight was necessary to characterize certain extract samples. For example, the acetate used in extraction number two tended to clog the ICP nebulizer without dilution.

## Results and Discussions

The first and second of the sequential extractions are generally viewed as conservative estimates of total available metal in the sample (Buchholz 1993). Extraction three simulates a reducing environment. Elements mobilized only in fraction four (moderately strong oxidation) should probably be considered unavailable in conventional disposal environments.

The ICP analysis intended to report levels of the following elements: Ag, Al, As, B, Ba, Be, Ca, Cd, Co, Cr, Cu, Fe, Hg, K, Li, Mg, Mn, Mo, Na, Ni, P, Pb, S, Sb, Se, Si, Sn, Sr, Ti, Tl, V, and Zn. The levels of certain elements, however, were below detection limits in various extracts. Appendix E lists concentration data, including detection limits.

Table 13 lists various detection limits in descending order. The largest detection limit of the four liquid extractions is reported for each element. Potassium, arsenic, and selenium typically have high ICP detection limits. All of the TCLP elements except for As and Se featured detection limits below 0.6 mg/L.

## TCLP Elements

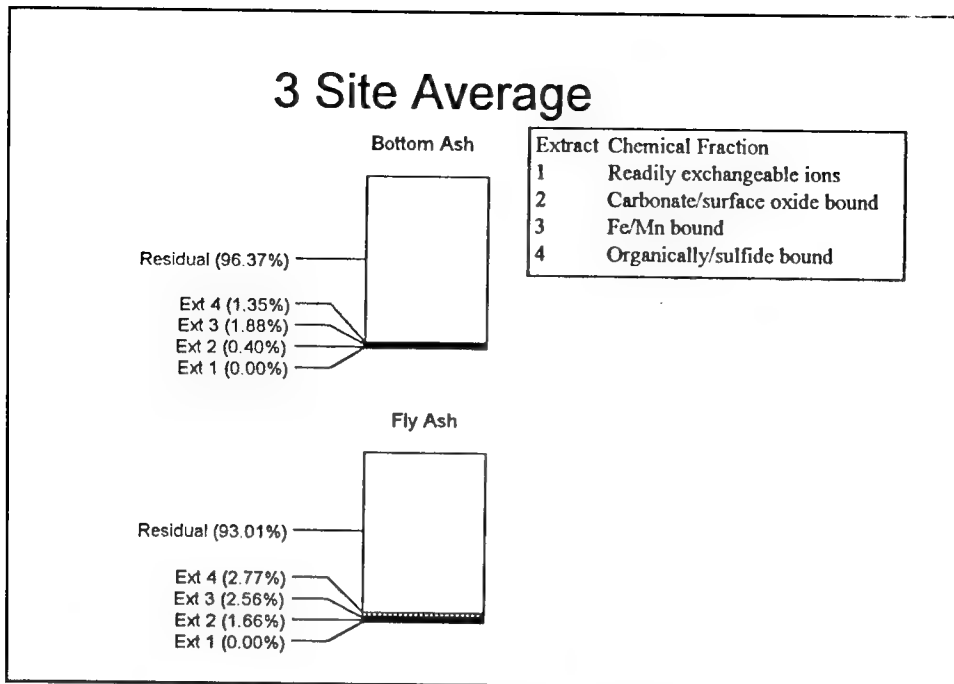
Some of the TCLP elements were present at levels below detection limits in the sequential extracts. Ag, As, and Hg were not found in any of the samples. Also, Se was found only in the "bound to Fe-Mn oxide" fraction of the Rock Island bottom ash. This isolated occurrence is suspect since the fly ash solids contained higher Se levels and would therefore be expected to leach detectable amounts as well. Detection limits for selenium, however, were higher than many of the other elements. Elements not detected in extracts are assumed to have remained unavailable during the sequence and to belong to the residual fraction.

Figure 28 shows extract data for chromium in fractional percentage form. The fraction of an element in a given extract is calculated by multiplying the liquid-to-solid ratio of the extract by the ratio of the concentration of the element in the extract to the ash concentration. The residual fraction was determined by subtracting the sum of the extract fractional percentages (one through four) from 100.

Table 13. Detection limits in sequential extraction liquid sample analysis.

Element	Detection Limit	Unit	Comments
Tl	3.0	mg/L	No levels detected
K	2.8	mg/L	Significant levels detected
P	2.45	mg/L	Significant levels detected
Sb	1.8	mg/L	No levels detected
As	1.65	mg/L	No levels detected
Se	1.2	mg/L	Detected in one extract
S	0.98	mg/L	Significant levels detected
Pb	0.59	mg/L	Minor levels detected
Sn	0.49	mg/L	Minor levels detected
Hg	0.46	mg/L	No levels detected
Mo	0.22	mg/L	Minor levels detected
Ni	0.17	mg/L	Levels detected
Ca	0.14	mg/L	High levels detected
Si	0.14	mg/L	Levels detected
B	0.13	mg/L	Levels detected
Al	0.10	mg/L	Levels detected
Cr	0.068	mg/L	Levels detected
Fe	0.058	mg/L	Levels detected
Co	0.044	mg/L	Levels detected
V	0.036	mg/L	Levels detected
Zn	0.034	mg/L	Levels detected
Ag	0.019	mg/L	No levels detected
Cd	0.016	mg/L	Minor levels detected
Mn	0.009	mg/L	Levels detected
Cu	0.007	mg/L	Levels detected
Li	0.007	mg/L	Levels detected
Ti	0.007	mg/L	Levels detected
Ba	0.003	mg/L	Levels detected
Be	0.001	mg/L	Minor levels detected
Sr	0.001	mg/L	Levels detected

Cr data is listed in Table E11 (Appendix E). Chromium in the ash samples did not seem to be readily exchangeable but levels were detected in the later fractions. The highest chromium levels were found in the Abbott fly ash sample extracts. Also, the fly ash featured more total leaching but, in both the bottom and fly ash, over 93 percent of the Cr remained in unavailable forms.



**Figure 28.** Cr extract concentrations expressed as fractions of the total amount in ash samples. (Average ash concentrations: 190 ppm [bottom ash]; 150 ppm [fly ash].)

Minor levels of Pb were detected in the extracts. Pb data are listed in Table E22. The most significant levels of Pb were detected in the Abbott fly ash extracts. Figure 29 lists lead data in fractional form. No Pb levels were found in the fourth fraction despite the low detection limit for that fraction (0.13 ppm). The data may be skewed towards the fractions with lower detection limits. For example, the Pb detection limit for the first extraction was 0.59 ppm while many of the reported concentrations from the second step are below this level, yet detectable, giving the second fraction a higher percent value. One could try using the detection limit values instead of zeroes in the fraction calculations, but this unfortunately guarantees that each fraction will always be represented when this may not be the case. This is one reason for caution in deciphering what the data truly indicate. In the current case, it can probably be said that bottom ash lead was not readily leachable and that not much Pb belonged to the organic/sulfide bound fraction. The general trend of fly ash leaching more than bottom ash was again demonstrated.

Barium data from the extracts are shown in Table E6. Since all samples contained detectable levels, fraction percentage determination was not hindered by the problems discussed in the Pb analysis. The concentrations of Ba in the sequential samples were the highest of the TCLP elements. Figure 30 shows the Ba data in fractional percentage form. The Abbott and Rock Island fly ash extract samples contained relatively higher Ba levels particularly in the carbonate/surface oxide and organic/sulfide bound fractions. Since Ba concentrations in the ash solids were



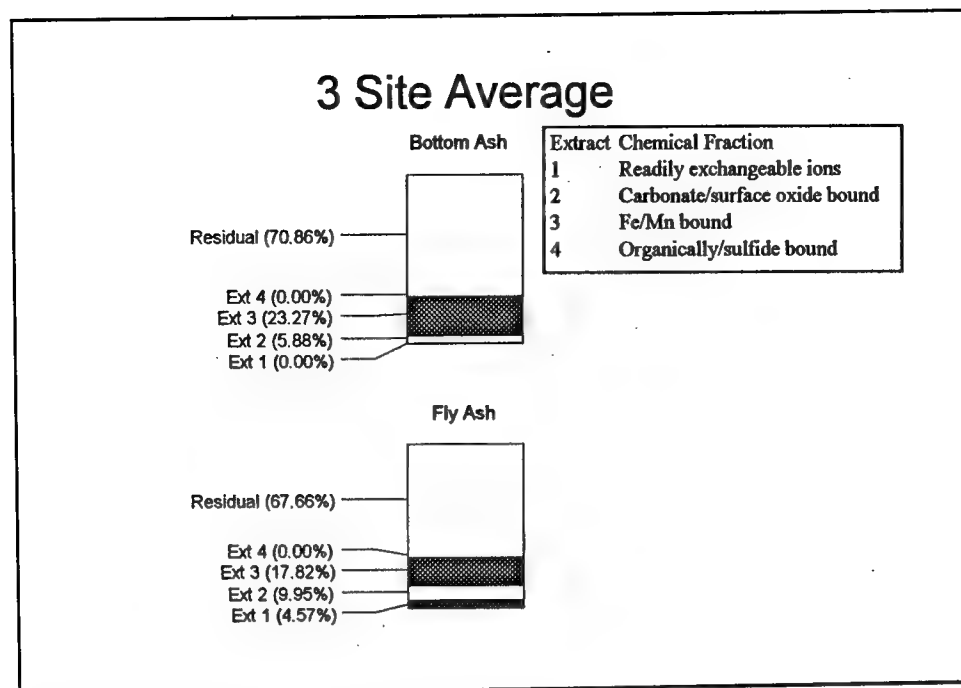


Figure 29. Pb extract concentrations expressed as fractions of the total amount in ash samples. (Average ash concentrations: 16 ppm [bottom ash]; 40 ppm [fly ash].)

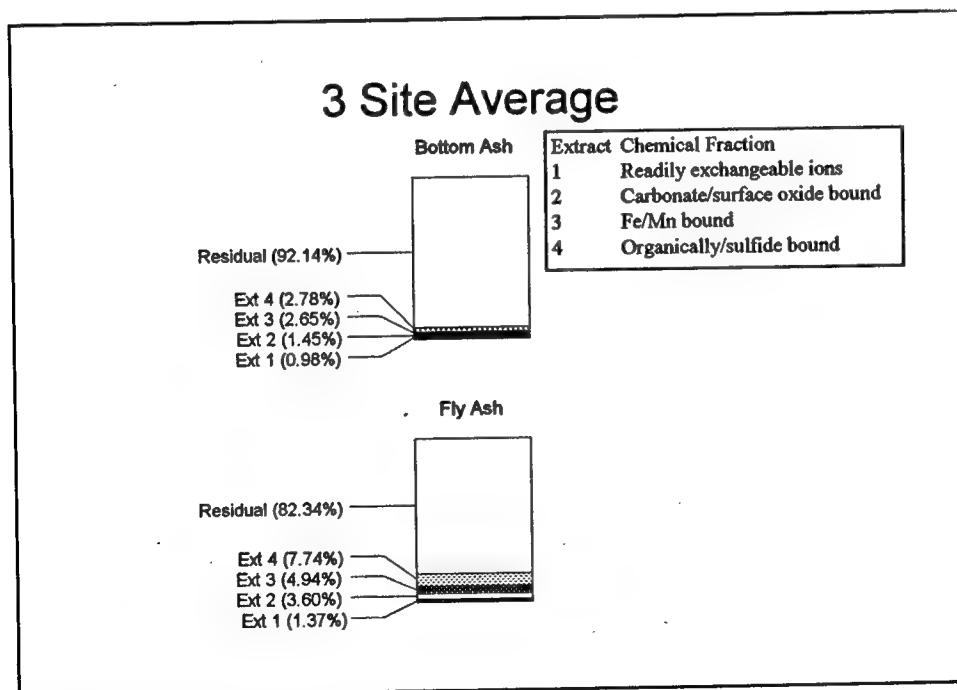


Figure 30. Ba extract concentrations expressed as fractions of the total amount in ash samples. (Average ash concentrations: 423 ppm [bottom ash]; 350 ppm [fly ash].)

moderately high (260 to 530 ppm), significant Ba was expected to exchange in fraction one (readily exchangeable ions). As expected, the fly ash samples retained less Ba than the bottom ash samples.

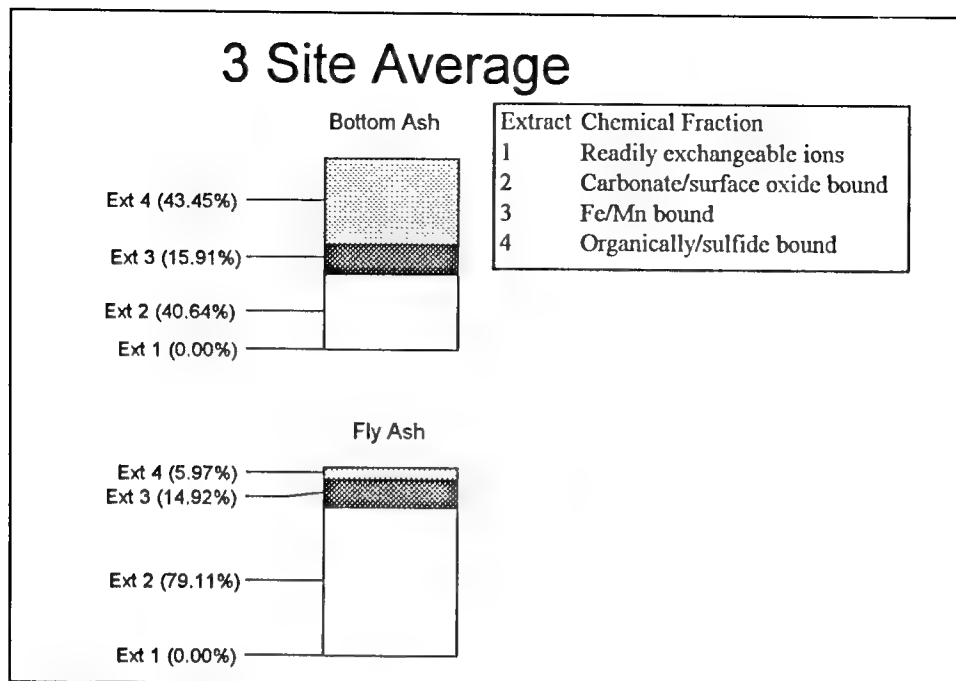


Figure 31. Fractional percentages of Cd in sequential extracts based on leached totals.

Cadmium data is listed in Table E9. The Abbott fly ash extracts contained the only appreciable level of cadmium (carbonate/surface oxide bound). According to the data, Cd would not be expected to leach readily or at sizable levels. Due to the lack of cadmium data from the ash solids, a different variety of fractional percentage graph was generated (Figure 31). It should be noted that these percentages are based only on the total leached Cd and not on the original ash concentrations. For example, roughly 40 percent of the leached (detectable) Cd in the bottom ash belonged to the second extraction (carbonate/surface oxide bound).

The previous figures have shown four of the eight TCLP elements, Ba, Cd, Cr, and Pb, to exhibit leaching behavior in the extracts. Of these elements, only Ba was detected at levels above 1 mg/L. Cd and Pb were detected in only about half of the sequential extracts. As and Se, however, were not detected, possibly due to high (> 1 mg/L) detection limits (Tables E4 and E25).

## Additional Elements

Elements not part of the regulatory statutes deserve attention as well. B, Be, Cu, Fe, Mo, Sb, S, Sn, Sr, and V are worthy of closer examination considering possible future regulatory changes. Most of the boron detected in the leachate samples belonged to

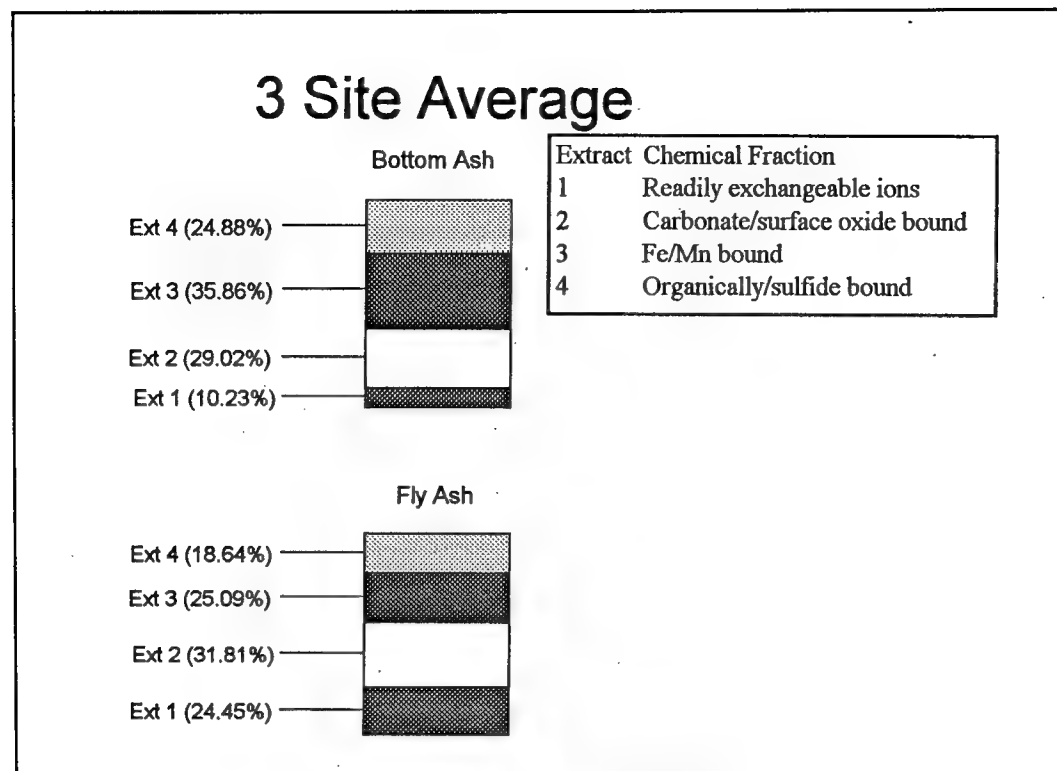


Figure 32. Fractional percentages of B in sequential extracts based on leached totals.

the carbonate/surface oxide bound fraction. Figure 32 shows boron data in fractional form. The fractions are again based on only the leached, detectable B and are therefore not based on initial or residual boron concentrations in the ash solids. Concentration data for B are listed in Table E5. All four fractions displayed boron leaching activity. Fly ash, particularly the Abbott sample, leached the most significant amounts of boron.

Low detection limits for Be in the extracts allowed the determination of minor levels. Concentration data is listed in Table E7. Figure 33 shows the fraction data based only on leached, detectable Be. Beryllium in the ash was not readily exchangeable and the majority of leached Be was detected in the third and fourth fractions. The levels involved, however, are very minor.

Cu and Fe leached into most of the fractions. Figure 34 shows copper percentage data. The absence of Cu in the first extracts indicates that copper in the ash is not readily exchangeable. According to the results, more than half of the Cu leached over the course of the four extractions. The organic/sulfide bound fraction leached by far the highest Cu levels. This is strong evidence that most of the copper is securely bound and will remain unavailable in conventional disposal applications. Figure 35 shows Fe percentage data. Iron in the ash samples, like copper, was not readily exchangeable. The Rock Island fly ash, however, leached relatively higher levels of Fe

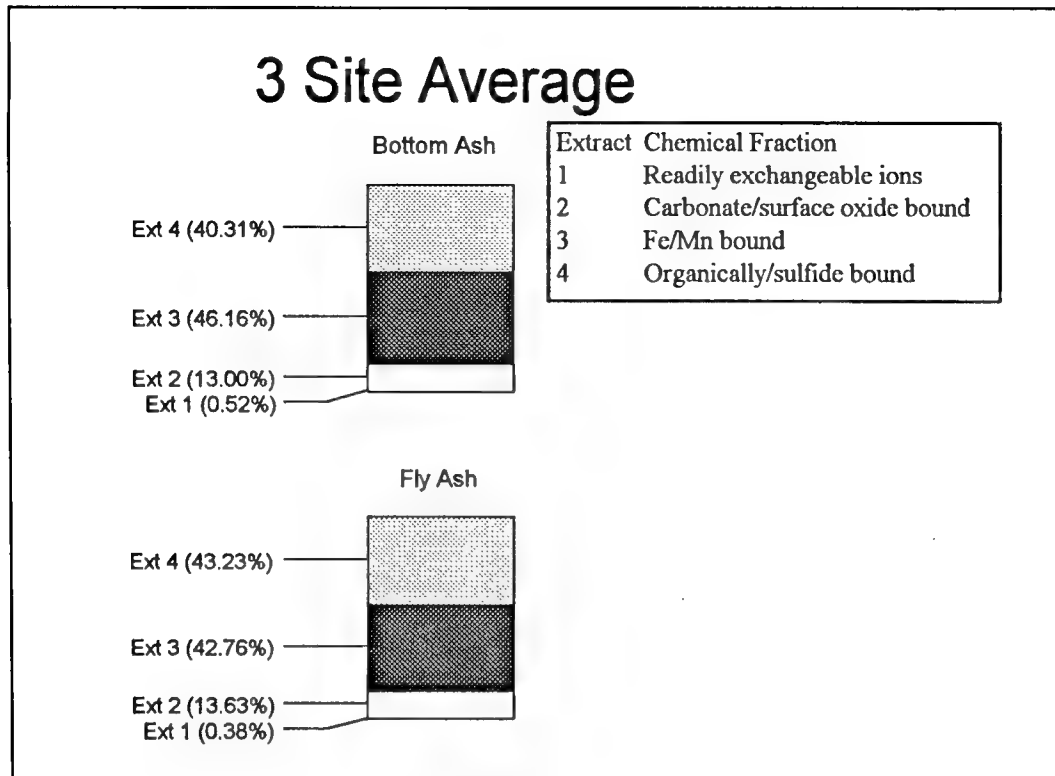


Figure 33. Fractional percentages of Be in sequential extracts based on leached totals.

in the first extract but lower levels in the remaining steps. Concentration data for Fe is listed in Table E13. The original ash solids contained Fe concentrations as high as 11.5 percent so one may expect high levels in the leachates. This was the case in fractions two, three, and four. There was, however, as expected, a reduction in Fe levels from fraction three (Fe/Mn bound) to fraction four (organic/sulfide bound). This suggests ash components bound to iron oxides were selectively (but not completely) attacked during extraction three.

Molybdenum concentration data are listed in Table E18. Only very minor levels were found. Fraction number four contained the most Mo but since only four out of 24 samples featured detectable Mo, not much information can be gained from fraction data. Results suggest that Mo would not pose a leaching problem in land disposal situations.

Sb and Tl were not detected in any extract samples. Detection limits for the various fractions for Sb and Tl are listed in Tables E24 and E30, respectively.

As expected, sulfur was detected in all leachates. The readily exchangeable fraction of the Abbott fly ash sample contained 875 mg/L of S (Table E23). Figure 36 shows fractional percentage data. Sulfur in the fly ash samples was apparently more readily

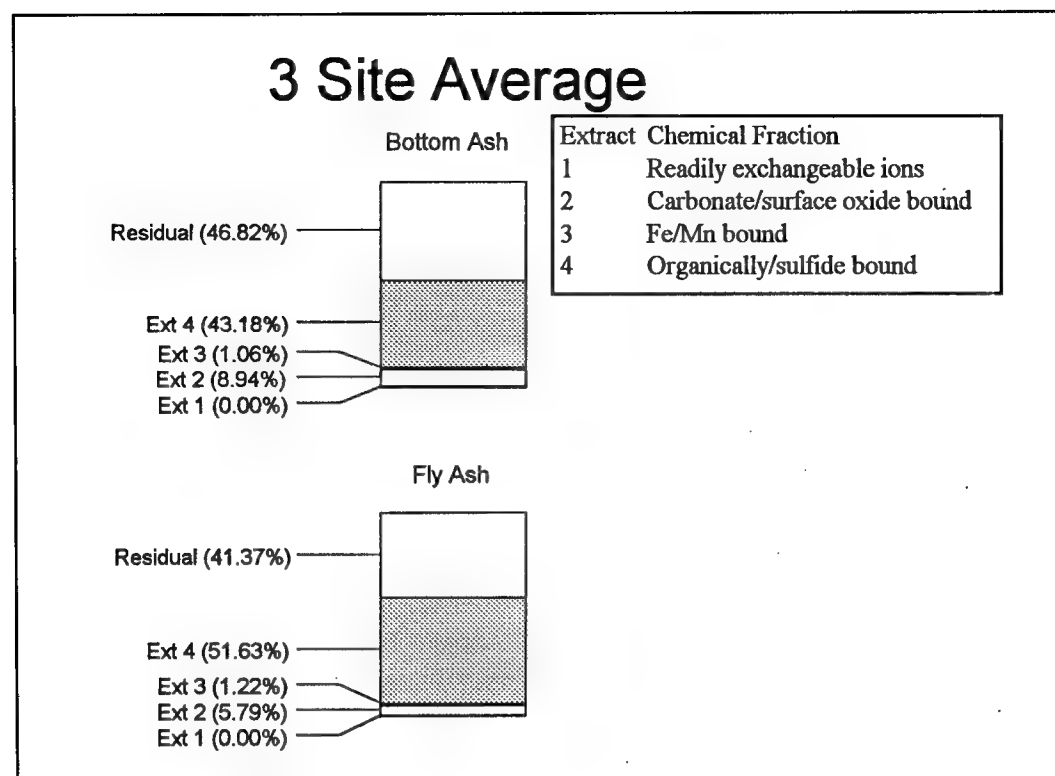


Figure 34. Cu percentage data from sequential extracts. (Average ash concentrations: 109 ppm [bottom ash]; 68 ppm [fly ash].)

exchangeable than the S in the bottom ash. The organic/sulfide bound extracts contained significantly more S than the second or third fractions.

Minor levels of Sn were detected (Table E27). For the most part, only the third fraction (bound to Fe-Mn oxides) contained tin. This is interesting because detection limits were reasonably low for the other fractions as well. The Rock Island ash, especially the bottom ash, leached the most tin.

Figure 37 shows fraction data for Sr in the sequential extracts. Differences between the fractions were not dramatic, but may indicate that Sr in the fly ash samples could be more readily exchangeable. Furthermore, the fly ash exhibited a greater degree of leaching compared to the bottom ash. Examination of the concentration levels in Table E28 shows the Rock Island fly ash leached higher Sr levels than the other ash varieties.

Levels of vanadium were found in certain extract fractions. Figure 38 shows relevant V data. The first fraction (readily exchangeable) failed to contain detectable V levels as did most of the second fraction extracts. V levels peaked during the third and fourth extract fractions. Concentration data in Table E32 shows the Rock Island fly ash to have released significantly more V than the other ash types. As expected, more V leached from fly ash than from bottom ash.

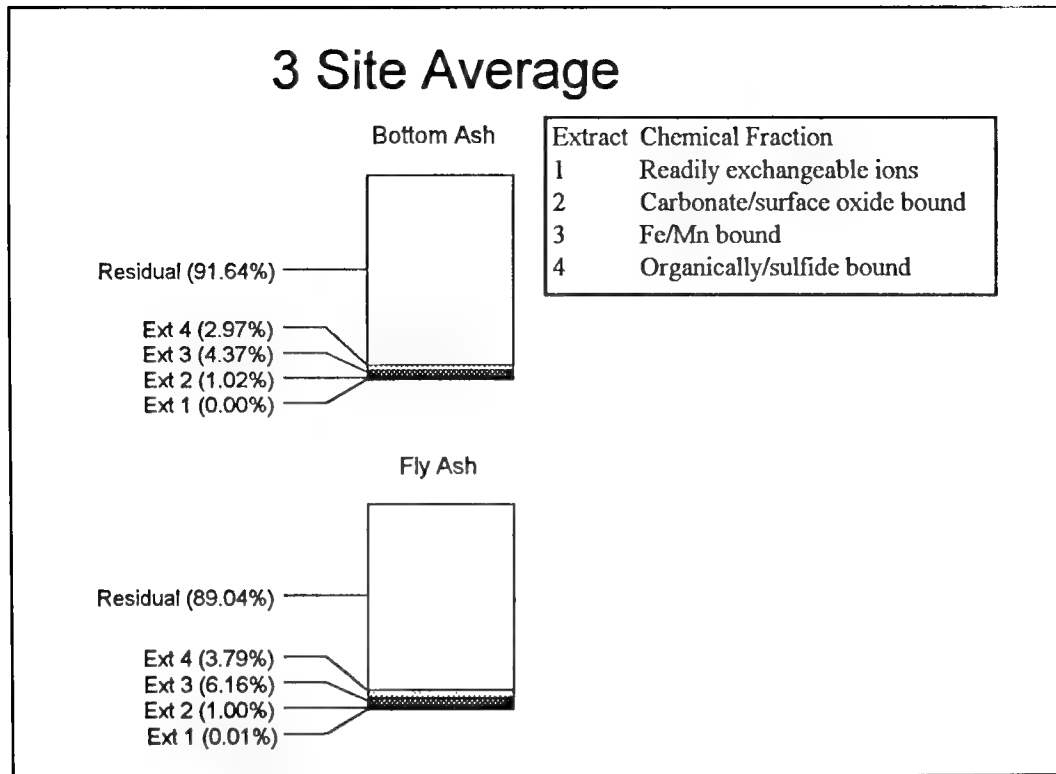


Figure 35. Fe percentage data from sequential extracts. (Average ash concentrations: 7.9% [bottom ash]; 6.8% [fly ash].)

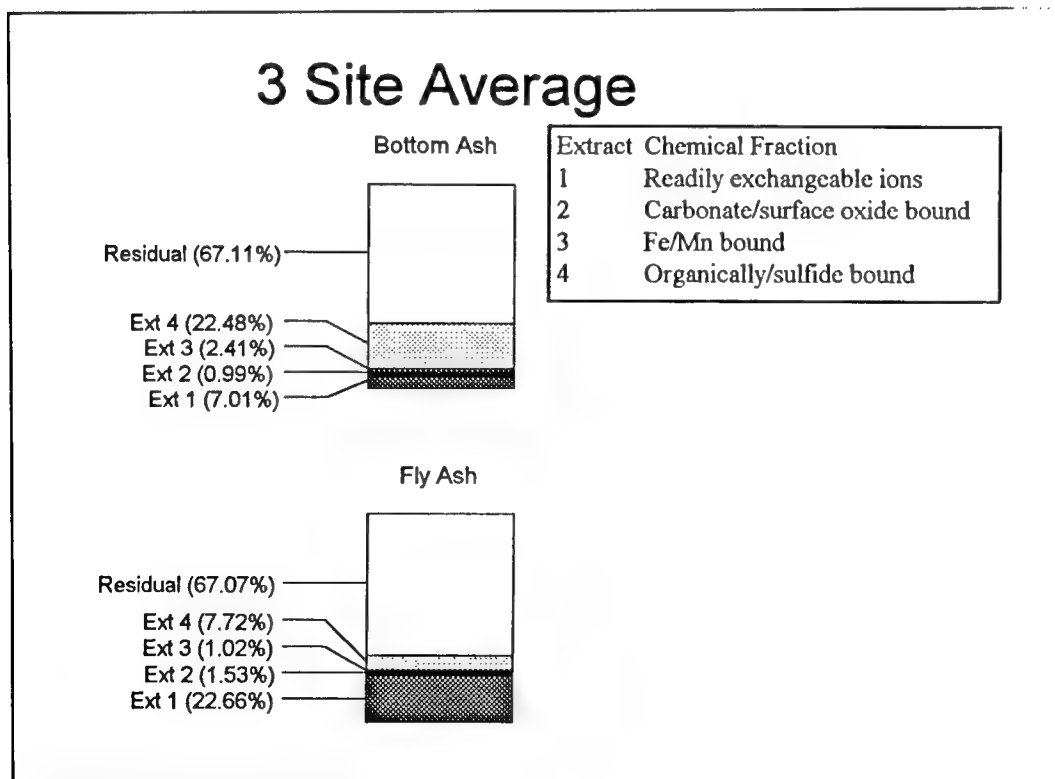


Figure 36. Fraction data for S in sequential extracts. (Average ash concentrations: 0.5% [bottom ash]; 1.2% [fly ash].)

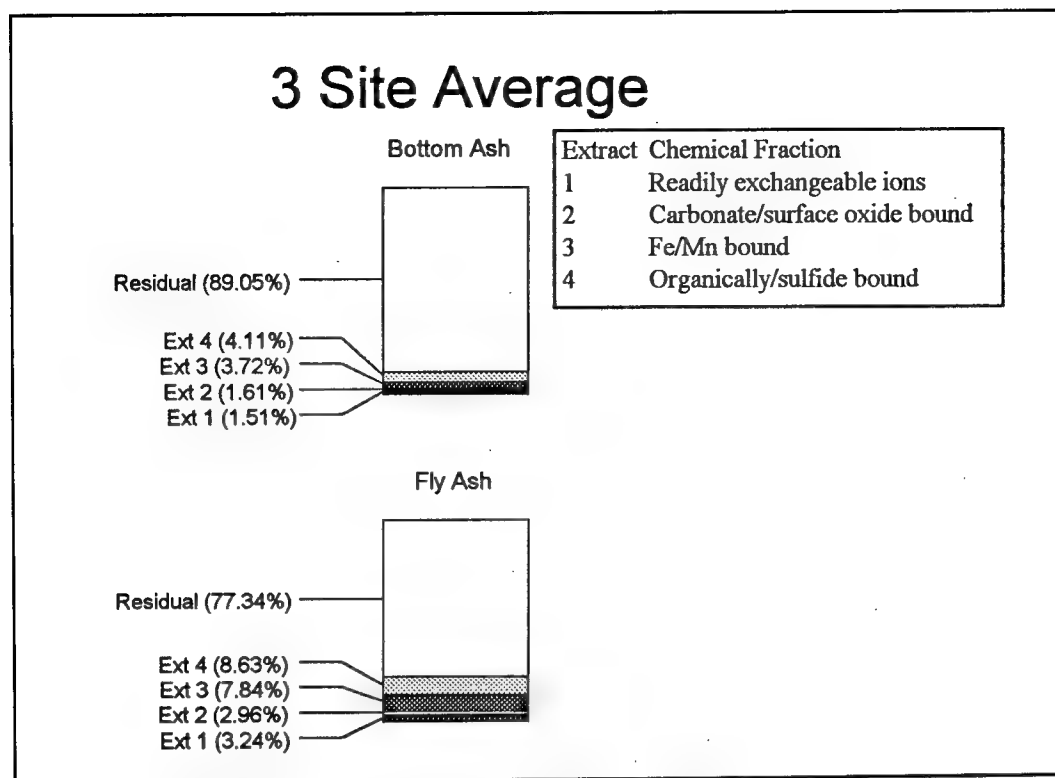


Figure 37. Fraction data for Sr in sequential extracts. (Average ash concentrations: 403 ppm [bottom ash]; 351 ppm [fly ash].)

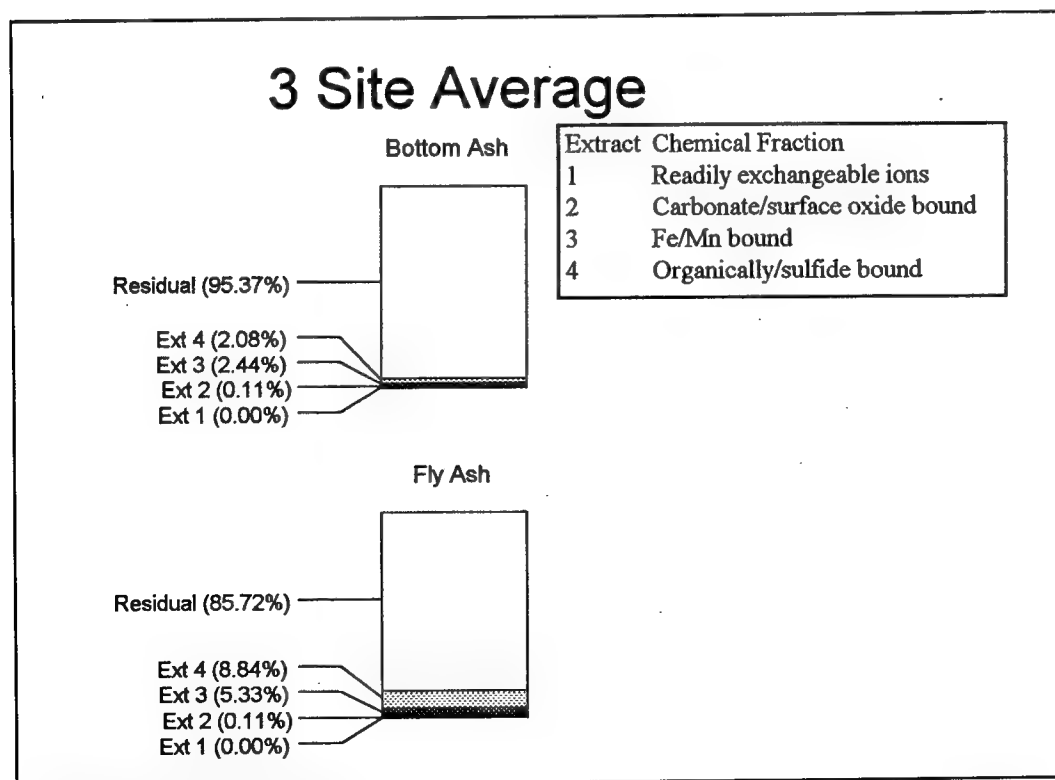


Figure 38. Fraction data for V in sequential extracts. (Average ash concentrations: 290 ppm [bottom ash]; 250 ppm [fly ash].)

Elements that exhibited relatively high amounts of leaching include Al, Si, Ca, K, and P. Aluminum levels reached as high as 159 mg/L (extraction four, Rock Island fly ash). Despite high levels of Al in the extract samples, the total percent leached only amounted to roughly 2 percent for the bottom ash and 5 percent for the fly ash. Al concentration data is listed in Table E3.

Silicon levels in the extracts reached as high as 143 mg/L (extract two, Abbott fly ash). As with aluminum, extraction four yielded the highest levels (Table E26). The data suggest that the fourth extraction featured the most severe attack of the aluminum and silicate components of the ash. This was expected since a moderately strong oxidant, 30 percent hydrogen peroxide, was involved in that step.

Ca levels in the samples were dramatic (Table E8). As anticipated, the readily exchangeable fraction leached the most calcium. Of the ash types in this study, the Abbott ash leached the most Ca. A flue-gas desulfurization process employing pulverized limestone ( $\text{CaCO}_3$ ) is used at the Abbott facility so high levels of both Ca and S would be expected. The process removes sulfur dioxide ( $\text{SO}_2$ ) from emissions, but produces large amounts of calcium sulfite,  $\text{CaSO}_3$  (s), in the ash. Since no worthwhile use has yet been found for the calcium sulfite, it is usually disposed in a landfill (Zumdahl 1993).

Potassium (MDL 2.8 mg/L) was detected in fractions one (readily exchangeable) and four (organic/sulfide bound) at moderately high levels (up to 126 mg/L). Potassium data are listed in Table E15. Phosphorus was extracted in fractions two (carbonate/surface oxide bound) through four (Table E21). However, the MDL for P in the first fraction was higher (2.45 mg/L) than the later fraction MDLs. Fraction four (bound to organics/sulfides) released the highest amounts of P into the extracts.

Levels of Co, Li, Mn, Ni, Ti, and Zn were also detected. Appendix E lists concentration data for these elements. Levels were generally minor. Some trends deserve attention, however. For example, Ni was not readily exchangeable, but was found at minor levels in later extracts (Table E20). High Ti levels appeared only in the fourth extract samples (organic/sulfide bound) (Table E29). Most of the detectable Zn was found in the second extracts (carbonate/surface oxide bound). Finally, Abbott ash leached substantially more Zn than the other varieties (Table E32).

Generally, the fly ash samples exhibited more substantial leaching than the bottom ash samples. This was expected due to the higher elemental concentrations of the fly ash solids compared to the bottom ash solids.



## 4 Discussion

### Bottom Ash

The following elements were at or below detection limits in all bottom ash leachate samples; Ag, As, Be, Cd, Co, Cu, Hg, Mn, Ni, P, Pb, Sb, Se, Sn, Ti, and Tl. Problems associated with leaching of the above elements in conventional land disposal would therefore not be expected. Barium and chromium were the only TCLP elements detected. The Abbott bottom ash leached much higher Ba levels initially than the Chanute and Rock Island varieties. Chromium levels were minor in all bottom ash leachates. The results of both the TCLP test and the water batch extractions indicate that none of the TCLP elements warrant concern for bottom ash leaching.

The elements that exhibited the most significant bottom ash leaching included in descending order: Ca, S, Si, Na, K, Al, Sr, and B. Additionally, Mo and V were detected in sample extracts. Mo exhibited lower leaching activity than V. Research has shown that Sr becomes enriched in soils and plants when exposed to coal ash but without apparent toxic effects (Keefer 1993). Also, toxic effects from vanadium, if any, have yet to be demonstrated. Of the above listed elements, perhaps the only elements of interest are S, B, and Mo. Abbott coal featured the highest sulfur content and this was reflected in the bottom ash leachate samples. Sulfur levels from the Chanute and Rock Island bottom ash leachate samples were substantially lower. Elevated sulfate concentrations at disposal ponds and fill sites is probably only a minor concern. The Chanute bottom ash samples leached the most B compared to the other two sites. B and Sr concentrations typically range from around 0.01 mg/L to 10 mg/L in groundwater (Freeze and Cherry 1979). Concentration peaks of B and Sr in certain bottom ash extract samples reached above 3 mg/L.

### Fly Ash

The following elements, including seven of the eight TCLP elements, were at or below detection limits in all leachate samples; Ag, As, Be, Cd, Co, Cr, Cu, Fe, Hg, Pb, Sb, Se, Sn, Ti, and Tl. Barium was the only TCLP element detected. Levels of Ba, however, were minor compared to the maximum allowable TCLP concentrations.

The elements that exhibited the most significant leaching from the fly ash included in descending order: S, Ca, Na, K, B, Si, Mg, Al, and Sr. Boron levels in the fly ash leachate samples were higher than in the bottom ash samples. S, Ca, Na, K, and B levels were highest in the Abbott fly ash leachate samples. Additionally, levels of Mo and V were detected.

Levels of B and Mo are not currently regulated in the TCLP test. Nevertheless, potential effects on plant and animal life due to elevated concentrations of these elements relating to land disposal should be considered. Boron is a nonmetal from group 3A and tends to form covalent bonds (Zumdahl 1993). Typical groundwater contains from 0.01 mg/L to 10 mg/L boron (Freeze and Cherry 1979). Average soils contain from 2 to 100 ppm of boron (Bowen 1966). Boron levels were not determined in the coal and ash solids involved in this study but as stated previously, relatively high concentrations appeared in leachate samples. Keefer (1993) lists typical concentrations for boron in coal and fly ash as 50 ppm and 370 ppm, respectively. Furthermore, boron levels in fly ash have reached as high as 5000 ppm. Many researchers have shown elevated concentrations of boron to potentially be toxic to plants (El-Mogazi et al. 1988). This toxicity should play a role in the permitting of coal ash utilization practices where vegetation may be adversely affected. Case-by-case decisions will probably be necessary as ash B content varies since certain species are not adversely affected by elevated boron concentrations.

Molybdenum levels can be toxic to animals consuming plants grown on ash-amended soil (Keefer 1993). Molybdenum is most stable in the +6 oxidation state and is chemically more available at higher pH levels (Keefer 1993). Groundwater typically contains less than 0.1 mg/L of Mo (Freeze and Cherry 1979), but Mo levels in average soil are about 2 ppm (Bowen 1966). Keefer (1993) suggests Mo concentrations in excess of 10 ppm may cause copper deficiencies in animals. Figure 39 shows molybdenum levels in average soil along with the average levels in the bottom and fly ash in the three sites examined in this study. Fly ash Mo levels averaged 10 times higher than typical soils.

## Sequential Extraction

The following elements were not detected in the sequential extracts: Ag, As, Hg, Sb, and Tl. Barium was the only TCLP element detected at levels above 1 mg/L. Barium in all ash tested was readily leachable and was expected to exchange easily in the first fraction as the ash solids contained between 260 and 530 ppm of Ba. Chromium was not readily leachable but leached into later fractions at minor levels. The minor levels of Pb detected were below the levels necessary to discuss with any degree of certainty.

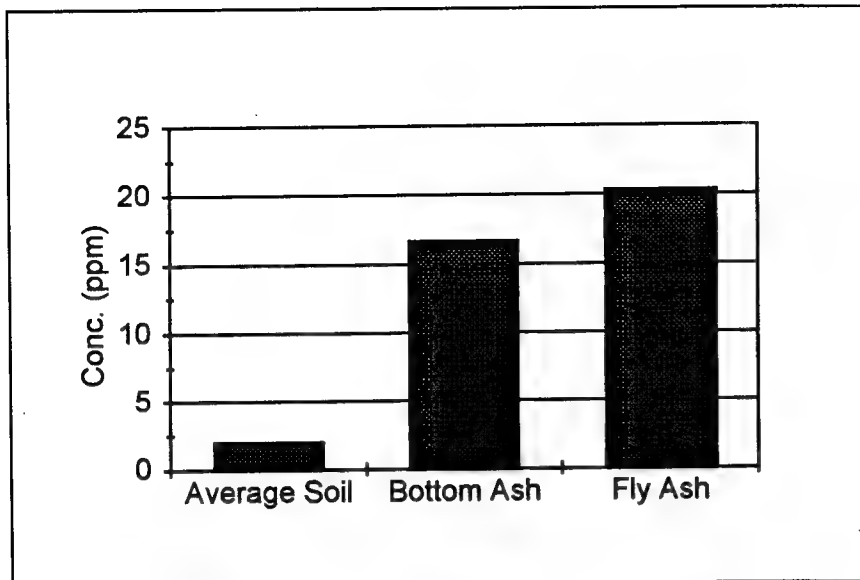


Figure 39. Average Mo levels in typical soil and ash from this study.

Selenium was found in only one extract and this single reported value was essentially at the detection limit or unreliable. Employing ICP-Mass Spectrometry may be a way of obtaining lower detection limits for Pb, As, and Se.

As, Hg, Se, and other contaminants with low boiling/sublimation points would most likely not pose a leaching problem from bottom ash. Forms of these elements usually vaporize during the coal combustion process and therefore only very minor amounts remain in the bottom ash. Oxides of the vaporized contaminants, however, could potentially become enriched by condensing onto fly ash particulates. Metal salts have a higher tendency to vaporize while certain metal oxides are less volatile. Of course, any vaporization of these contaminants is of vital importance to maintaining emission air quality. Mercury was not detected in any of the coal samples (Appendix B). The Rock Island selenium data from the coal and ash characterizations show concentration reductions from coal to bottom ash but enrichment from coal to fly ash. Selenium was not detectable in the bottom ash of the Chanute and Rock Island sites. Arsenic data from all three sites showed similar volatilization trends.

Certain elements in addition to the TCLP contaminants deserve attention. Boron was detected in all extracts; the most boron seemed to leach from fraction two (carbonate/surface oxide bound). Minor levels of Be were detected but only in the later fractions. Recall that fraction four (organic/sulfide bound) featured leaching conditions more aggressive than those found in conventional landfill environments. Copper was not readily leachable (fraction one) but did appear in fraction four (organic/sulfide bound). Fe was likewise not readily leachable (fraction one). Minor levels of Mo were detected in one sixth of the samples. Large amounts of sulfur were detected in fractions one (readily exchangeable) and four (organic/sulfide bound). Minor levels of

Sn leached into fraction three (Fe/Mn bound). The Rock Island site leached the most Sr compared to the other sites. Vanadium was not readily leachable but did appear in fractions three and four. Al, Si, Ca, K and P featured relatively high amounts of leaching. Minor levels of Co, Li, Mn, Ni, Ti, and Zn were also detected. As expected, the fly ash samples exhibited increased leaching activity over the bottom ash samples.

Allowable disposal methods for individual states are listed in Table F1 (Appendix F). The list was compiled during the spring of 1994, but state codes are subject to frequent revision particularly in response to the recent (August 1993) continuation of the Federal (RCRA) hazardous waste exemption.

Generators of coal ash residues seek disposal and or utilization opportunities that present minimal costs. Disposal at or near the site of generation is desirable. In some cases, ash may be given away or even sold to local highway departments or materials manufacturers. All of these are valid options provided necessary regulations are satisfied. In any case, hauling material back to the original mine hundreds of miles away is often neither reasonable nor necessary. The results of this study indicate disposal in either municipal landfills or ash monofills would be satisfactory as far as leaching of the regulated metals is concerned.

According to this study, the elements of concern are the eight TCLPs: Ag, As, Ba, Cd, Cr, Hg, Pb, Se, and also B and Mo. Bottom ash and fly ash should be treated separately when considering disposal options since fly ash is more likely to exceed regulatory limits than bottom ash and combining the two may cause violations. Because bottom ash is usually produced in larger amounts than fly ash, separation of the two may result in lower disposal costs (Pfeffer 1992).

## 5 Conclusions and Recommendations

### Conclusions

Laboratory leaching procedures combined with neutron activation analysis (NAA), and inductively coupled plasma-atomic emission spectroscopy (ICP-AES), allowed the examination of a wide range of elements in coal and ash samples and in ash leachates. The obtained results indicate the potential hazards of disposal of ash varieties considered in this study.

#### *Water Batch Extraction*

All ash samples employed in this study successfully passed the TCLP test from an inorganic contaminant standpoint. Accordingly, the levels of the TCLP elements in the water batch extracts were in most cases far below the regulated levels. This is especially true for barium where the regulatory level is highest (100 mg/L).

This study concludes that the examined ash varieties are not likely to leach high concentrations of TCLP elements when landfilled. Boron and sulfur, however, leached at higher levels than the TCLP elements. Furthermore, elevated levels of naturally occurring soil elements may not result in readily apparent effects, even though such levels may be toxic to soil microbial communities and vegetation.

#### *Bottom Ash*

The results of both the TCLP test and the water batch extractions indicate none of the TCLP elements warrant concern for bottom ash leaching.

#### *Fly Ash*

Levels of B and Mo are not currently regulated in the TCLP test. Nevertheless, potential toxic effects on plant and animal life due to elevated concentrations of these elements relating to land disposal should be considered. This toxicity should play a role in the permitting of coal ash utilization practices in which vegetation may be

adversely affected. Case-by-case decisions will probably be necessary as ash B content varies since certain species are not adversely affected by elevated boron concentrations.

Molybdenum levels can be toxic to animals consuming plants grown on ash-amended soil. Fly ash Mo levels averaged 10 times higher than typical soils.

### ***Sequential Extraction Conclusions***

As, Hg, and Se and other contaminants with low boiling/sublimation points would most likely not pose a leaching problem from bottom ash. Forms of these elements usually vaporize during the coal combustion process and therefore only very minor amounts remain in the bottom ash. Oxides of the vaporized contaminants, however, could potentially become enriched through condensing onto fly ash particulates. Metal salts have a higher tendency to vaporize while certain oxides of metals are less volatile. Any vaporization of these contaminants is of vital importance to maintaining emission air quality.

### **Recommendations**

The results of this study indicate that disposal in either municipal landfills or ash monofills would be satisfactory as far as leaching of the regulated metals is concerned. Generators of coal ash residues seek disposal and or utilization opportunities that present minimal costs. Disposal at or near the site of generation is desirable. In some cases, ash may be given away or even sold to local highway departments or materials manufacturers. All of these are valid options provided necessary regulations are satisfied. In any case, back hauling material to the original mine hundreds of miles away is often not a reasonable or necessary solution.

This study recommends that utilization and disposal practices in which contaminants may be more available to vegetation or exposed directly to precipitation and or substantial runoff be allowed, provided that adequate stabilization of toxic contaminants can be demonstrated, for example, by soil amendment or retaining wall construction.

Since, according to this study, the elements of concern are the eight TCLP ones; Ag, As, Ba, Cd, Cr, Hg, Pb, Se, and also B and Mo, it is recommended that bottom ash and fly ash be treated separately when considering disposal options. Fly ash from a site is more likely to exceed regulatory limits than bottom ash and combining the two may

cause violations. Due to the fact that bottom ash is usually produced in larger amounts than fly ash, separation of the two may result in lower disposal costs.

### Further Research

Since this study examined only elemental levels in coal and ash samples from three sites, more site-specific studies are recommended to help coal-fired plants meet the requirements of the 1990 Clean Air Act amendments. For example, investigations combining thorough elemental characterization of coal and ash with flue gas emission sampling to study volatilization of Hg, As, Se, and other contaminants seem appropriate. Furthermore, leaching experiments, both field and laboratory, should continue to help determine the suitability of specific utilization practices. Also, additional studies examining the bioavailability of B and Mo from coal residues could only be beneficial. Research should continue into the possible effects of inorganics not currently regulated since future regulations may conceivably involve Be, B, Mo, Sb, and Sn in the permitting of certain utilization options.

The results obtained from this study support the recent continuation of the coal ash waste exemption from Federal hazardous waste regulation (RCRA). Individual states, however, may continue to require that certain specific ash tests be performed and that other restrictions be satisfied before allowing certain disposal practices. For example, a certain lack of mobility of inorganic contaminants may have to be demonstrated. Further studies of coal ash leaching behavior are recommended for their anticipated role in determining appropriate disposal and utilization methods for coal ash residues.

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## Appendix A: List of Chemical Elements

### Symbol Element

Ac actinium  
Al aluminum  
Am americium  
Sb antimony  
Ar argon  
As arsenic  
At astatine  
Ba barium  
Bk berkelium  
Be beryllium  
Bi bismuth  
B boron  
Br bromine  
Cd cadmium  
Ca calcium  
Cf californium  
C carbon  
Ce cerium  
Cs cesium  
Cl chlorine  
Cr chromium  
Co cobalt  
Cu copper  
Cm curium  
Dy dysprosium  
Es einsteinium  
Er erbium  
Eu europium  
Fm fermium  
F fluorine  
Fr francium  
Gd gadolinium  
Ga gallium  
Ge germanium  
Au gold  
Hf hafnium

### Symbol Element

He helium  
Ho holmium  
H hydrogen  
In indium  
I iodine  
Ir iridium  
Fe iron  
Kr krypton  
La lanthanum  
Lr lawrencium  
Pb lead  
Li lithium  
Lu lutetium  
Mg magnesium  
Mn manganese  
Md mendelevium  
Hg mercury  
Mo molybdenum  
Nd neodymium  
Ne neon  
Np neptunium  
Ni nickel  
Nb niobium  
N nitrogen  
No nobelium  
Os osmium  
O oxygen  
Pd palladium  
P phosphorus  
Pt platinum  
Pu plutonium  
Po polonium  
K potassium  
Pr praseodymium  
Pm promethium

### Symbol Element

Pa protactinium  
Ra radium  
Rn radon  
Re rhenium  
Rh rhodium  
Rb rubidium  
Ru ruthenium  
Sm samarium  
Sc scandium  
Se selenium  
Si silicon  
Ag silver  
Na sodium  
Sr strontium  
S sulfur  
Ta tantalum  
Tc technetium  
Te tellurium  
Tb terbium  
Tl thallium  
Th thorium  
Tm thulium  
Sn tin  
Ti titanium  
W tungsten  
Unh unnilhexium  
Unp unnilpentium  
Unq unnilquadium  
U uranium  
V vanadium  
Xe xenon  
Yb ytterbium  
Y yttrium  
Zn zinc  
Zr zirconium

## Appendix B: Elemental Concentrations in Coal

This appendix lists the concentrations of elements in the Abbott, Chanute, and Rock Island coal samples. Cu, Ni, Pb, S, Zr, and Zn were analyzed with X-ray florescence methods. All other elements were analyzed with neutron activation analysis (NAA).

**Table B1. Abbott coal.**

Element	Conc.	±	Unit	Detection Limit
Ag	0	0	ppm	0.4
Al	1.2	0.1	%	0.1
As	5.1	0.2	ppm	0.4
Ba	52	10	ppm	29
Br	10	1	ppm	2
Ca	0.69	0.03	%	0.01
Ce	6.3	0.4	ppm	1.1
Cl	1500	60	ppm	12
Co	2.4	0.1	ppm	0.1
Cr	22.5	0.1	ppm	2.5
Cs	1.0	0.04	ppm	0.1
Cu	12.0	2	ppm	0.1
Dy	0.8	0.1	ppm	0.1
Fe	1.79	0.03	%	0.01
Hg	0	0	ppm	0.5
In	0	0	ppb	12
I	1.5	0.2	ppm	0.6
K	0.22	0.03	%	0.07
La	4.4	0.1	ppm	0.1
Mn	86	4	ppm	1
Mo	N/A	N/A	N/A	N/A
Na	1250	80	ppm	19
Ni	16	2	ppm	N/A
Pb	4	1	ppm	N/A
Rb	15.5	2.5	ppm	7.9

Element	Conc.	±	Unit	Detection Limit
S	4.1	0.6	%	N/A
Sb	0.8	0.2	ppm	0.1
Sc	2.2	0.03	ppm	0.1
Se	2.4	0.3	ppm	0.9
Si	4.3	0.4	%	1
Sm	1.07	0.01	ppm	0.02
Sr	41	13	ppm	40
Ta	0.14	0.01	ppm	0.03
Th	1.38	0.06	ppm	0.17
Ti	700	50	ppm	100
U	2.9	0.1	ppm	0.3
V	30	1	ppm	1
Zn	56	8	ppm	N/A
Zr	N/A	N/A	N/A	N/A

Table B2. Chanute coal.

Element	Conc.	±	Unit	Detection Limit
Ag	0	0	ppm	0.5
Al	1.2	0.1	%	0.01
As	6.6	0.2	ppm	0.5
Ba	51.0	7.1	ppm	19.5
Br	0	0	ppm	1.4
Ca	0.08	0.01	%	0.01
Ce	25.7	0.7	ppm	1.5
Cl	99	5	ppm	5
Co	14.3	0.2	ppm	0.1
Cr	16.1	1.0	ppm	3.2
Cs	0.66	0.04	ppm	0.13
Cu	19	3	ppm	N/A
Dy	1.5	0.1	ppm	0.1
Fe	0.61	0.01	%	0.01
Hg	0	0	ppm	0.5
In	8	3	ppb	8
I	1.5	0.2	ppm	0.6
K	0.11	0.02	%	0.1
La	15.6	0.2	ppm	0.1

Element	Conc.	±	Unit	Detection Limit
Mn	17.5	0.8	ppm	0.4
Mo	N/A	N/A	N/A	N/A
Na	256	16	ppm	13
Ni	11	2	ppm	N/A
Pb	18	3	ppm	N/A
Rb	6.8	2.9	ppm	9.5
S	1.5	0.2	%	N/A
Sb	1.05	0.02	ppm	0.05
Sc	4.9	0.1	ppm	0.1
Se	4.0	0.4	ppm	1.1
Si	1.7	0.3	%	0.9
Sm	3.73	0.04	ppm	0.02
Sr	86	10	ppm	27
Ta	0.11	0.02	ppm	0.04
Th	2.0	0.1	ppm	0.2
Ti	617	36	ppm	60
U	0.9	0.1	ppm	0.3
V	29.4	0.7	ppm	0.8
Zn	66	10	ppm	N/A
Zr	N/A	N/A	N/A	N/A

Table B3. Rock Island coal.

Element	Conc.	±	Unit	Detection Limit
Ag	0	0	ppm	0.5
Al	1.8	0.1	%	0.1
As	7.8	0.2	ppm	0.5
Ba	69	8	ppm	20
Br	16	1	ppm	1
Ca	0.09	0.01	%	0.01
Ce	17.1	0.5	ppm	1.4
Cl	818	34	ppm	6
Co	8.5	0.2	ppm	0.1
Cr	25	1	ppm	3
Cs	1.12	0.04	ppm	0.12
Cu	9.0	1.4	ppm	N/A
Dy	2.4	0.2	ppm	0.1

Element	Conc.	±	Unit	Detection Limit
Fe	0.59	0.01	%	0.1
Hg	0	0	ppm	0.5
In	17	3	ppb	9
I	2.03	0.15	ppm	0.39
K	0.18	0.02	%	0.06
La	10.2	0.1	ppm	0.4
Mn	9.2	0.5	ppm	0.5
Mo	N/A	N/A	N/A	N/A
Na	213	14	ppm	13
Ni	4	1	ppm	N/A
Pb	10.0	1.5	ppm	N/A
Rb	0	0	ppm	8
S	1.7	0.3	%	N/A
Sb	1.12	0.02	ppm	0.04
Sc	5.0	0.1	ppm	0.1
Se	5.6	0.3	ppm	1.0
Si	3.2	0.4	%	0.9
Sm	2.48	0.03	ppm	0.02
Sr	55.0	9.3	ppm	28.1
Ta	0.22	0.01	ppm	0.04
Th	3.22	0.08	ppm	0.18
Ti	920	50	ppm	70
U	1.9	0.1	ppm	0.3
V	48.4	1.1	ppm	1.0
Zn	18.0	2.7	ppm	N/A
Zr	N/A	N/A	N/A	

## Appendix C: Elemental Concentrations in Ash

This appendix lists the concentrations of elements in the Abbott, Chanute, and Rock Island coal ash samples. Cu, Mo, Ni, Pb, S, Zr, and Zn were analyzed with X-ray florescence methods. All other elements were analyzed with neutron activation analysis (NAA).

**Table C1. Abbott bottom ash.**

Element	Conc.	±	Unit	Detection Limit
Ag	0	0	ppm	0.8
Al	8.3	0.6	%	0.1
As	4.0	0.2	ppm	0.8
Ba	333	34	ppm	80
Br	0	0	ppm	8
Ca	4.5	0.1	%	0.1
Ce	54.9	1.1	ppm	2.0
Cl	24.6	10.7	ppm	14.9
Co	16.3	0.2	ppm	0.1
Cr	214	3	ppm	5
Cs	5.8	0.1	ppm	0.2
Cu	68.0	10.2	ppm	N/A
Dy	5.2	0.4	ppm	0.4
Fe	11.5	0.2	%	0.1
Hg	0	0	ppm	1
In	0	0	ppb	36
I	0	0	ppm	2
K	1.6	0.1	%	0.2
La	33.6	0.4	ppm	0.1
Mn	573	26	ppm	3
Mo	29.0	4.4	ppm	N/A
Na	6800	400	ppm	40
Ni	122	18	ppm	N/A
Pb	10.0	1.5	ppm	N/A
Rb	91.1	4.9	ppm	14.8
S	0.63	0.10	%	N/A



Element	Conc.	±	Unit	Detection Limit
Sb	1.84	0.03	ppm	0.07
Sc	15.3	0.2	ppm	0.1
Se	3.3	0.5	ppm	1.651
Si	25.0	2.0	%	4
Sm	7.7	0.1	ppm	0.1
Sr	223.1	36.3	ppm	110.0
Ta	0.88	0.03	ppm	0.06
Th	10.0	0.2	ppm	0.3
Ti	4410	250	ppm	380
U	24.7	0.6	ppm	0.5
V	211	5	ppm	5
Zn	553	83	ppm	N/A
Zr	133	20	ppm	N/A

Table C2. Chanute bottom ash.

Element	Conc.	±	Unit	Detection Limit
Ag	0	0	ppm	1
Al	13.2	0.9	%	0.2
As	6.0	0.4	ppm	1.4
Ba	407	31	ppm	31
Br	0	0	ppm	4
Ca	0.67	0.03	%	0.02
Ce	226	4	ppm	4
Cl	9.5	4.2	ppm	13.6
Co	106.6	1.5	ppm	0.2
Cr	161.7	3.5	ppm	8.2
Cs	6.3	0.1	ppm	0.4
Cu	115	17	ppm	N/A
Dy	14.2	1.1	ppm	0.2
Fe	6.7	0.1	%	0.1
Hg	0	0	ppm	1
In	13.5	4.3	ppb	13.6
I	0	0	ppm	1
K	1.2	0.1	%	0.1
La	145.1	1.7	ppm	0.3
Mn	161.7	7.4	ppm	0.9
Mo	6.0	0.9	ppm	N/A
Na	2340	140	ppm	13

Element	Conc.	±	Unit	Detection Limit
Ni	275	41	ppm	N/A
Pb	15.0	2.3	ppm	N/A
Rb	90.3	7.4	ppm	23.5
S	0.5	0.1	%	N/A
Sb	2.27	0.05	ppm	0.13
Sc	43.0	0.5	ppm	0.1
Se	0	0	ppm	3
Si	18.1	1.5	%	3.1
Sm	30.5	0.3	ppm	0.8
Sr	547.3	33.2	ppm	40.0
Ta	1.25	0.04	ppm	0.12
Th	21.3	0.3	ppm	0.5
Ti	5350	290	ppm	360
U	7.4	0.3	ppm	0.9
V	284	7	ppm	6
Zn	35	5	ppm	N/A
Zr	153	23	ppm	N/A

Table C3. Rock Island bottom ash.

Element	Conc.	±	Unit	Detection Limit
Ag	0	0	ppm	1.4
Al	16.4	1.2	%	0.1
As	6.3	0.4	ppm	1.3
Ba	530	40	ppm	60
Br	0	0	ppm	5
Ca	0.62	0.03	%	0.02
Ce	136.1	2.6	ppm	3.6
Cl	20.5	6.0	ppm	19.1
Co	62.7	0.9	ppm	0.1
Cr	194.2	3.7	ppm	7.7
Cs	8.5	0.2	ppm	0.3
Cu	144	22	ppm	N/A
Dy	18.2	1.4	ppm	0.3
Fe	5.5	0.1	%	0.1
Hg	0	0	ppm	1
In	29.3	7.6	ppb	23.6
I	0	0	ppm	1
K	1.6	0.1	%	0.1

Element	Conc.	±	Unit	Detection Limit
La	86.7	1.0	ppm	0.2
Mn	94.5	4.4	ppm	1.1
Mo	15.0	2.3	ppm	N/A
Na	1570	90	ppm	26
Ni	111	17	ppm	N/A
Pb	24.0	3.600	ppm	N/A
Rb	97.0	6.6	ppm	20.5
S	0.25	0.04	%	N/A
Sb	4.3	0.1	ppm	0.1
Sc	42	1	ppm	0.1
Se	0	0	ppm	3
Si	24.6	1.9	%	3.4
Sm	18.2	0.2	ppm	0.1
Sr	437.8	34.0	ppm	70.0
Ta	1.64	0.04	ppm	0.11
Th	27.9	0.4	ppm	0.5
Ti	7510	390	ppm	360
U	14.1	0.4	ppm	0.8
V	374	8	ppm	6
Zn	54	8	ppm	N/A
Zr	216	32	ppm	N/A

Table C4. Abbott fly/bottom ash.

Element	Conc.	±	Unit	Detection Limit
Ag	0	0	ppm	1
Al	6.9	0.5	%	0.1
As	31.6	0.5	ppm	0.9
Ba	354	35	ppm	80
Br	0	0	ppm	8
Ca	3.8	0.1	%	0.1
Ce	32.8	0.9	ppm	2.1
Cl	58.8	11.6	ppm	36.4
Co	15.5	0.2	ppm	0.1
Cr	162.5	2.8	ppm	4.8
Cs	5.8	0.1	ppm	0.2
Cu	62	9	ppm	N/A
Dy	4.8	0.4	ppm	0.4
Fe	11.4	0.2	%	0.1

Element	Conc.	±	Unit	Detection Limit
Hg	0.8	0.2	ppm	0.7
In	64.6	12.8	ppb	38.3
I	0	0	ppm	2
K	1.2	0.1	%	0.2
La	26.9	0.3	ppm	0.1
Mn	521	24	ppm	3
Mo	41	6	ppm	N/A
Na	7600	500	ppm	40
Ni	95	14	ppm	N/A
Pb	45	7	ppm	N/A
Rb	83.4	5.1	ppm	15.7
S	2.3	0.3	%	N/A
Sb	6.2	0.1	ppm	0.1
Sc	13.9	0.2	ppm	0.1
Se	8.8	0.5	ppm	1.7
Si	22.5	1.8	%	3.5
Sm	6.3	0.1	ppm	0.1
Sr	173	37.4	ppm	120
Ta	0.94	0.03	ppm	0.07
Th	9.2	0.2	ppm	0.3
Ti	3970	220	ppm	340
U	19.0	0.5	ppm	0.5
V	177.8	4.1	ppm	3.8
Zn	693	104	ppm	N/A
Zr	119	18	ppm	N/A

Table C5. Chanute fly ash.

Element	Conc.	±	Unit	Detection Limit
Ag	0	0	ppm	1
Al	6.7	0.5	%	0.1
As	25.5	0.5	ppm	1.3
Ba	262	28	ppm	70
Br	0	0	ppm	5
Ca	0.71	0.03	%	0.02
Ce	137	3	ppm	4
Cl	28.4	6.0	ppm	18.5
Co	103.4	1.5	ppm	0.2
Cr	119.2	2.9	ppm	7.3

Element	Conc.	±	Unit	Detection Limit
Cs	3.0	0.1	ppm	0.3
Cu	67	10	ppm	N/A
Dy	10.2	0.8	ppm	0.3
Fe	5.5	0.1	%	0.1
Hg	0	0	ppm	1
In	0	0	ppb	33
I	0	0	ppm	1
K	0.6	0.1	%	0.2
La	90.4	1.1	ppm	0.2
Mn	127	6	ppm	1
Mo	4.0	0.6	ppm	N/A
Na	1570	100	ppm	40
Ni	297	45	ppm	N/A
Pb	33	5	ppm	N/A
Rb	47.2	7.2	ppm	23.3
S	0.7	0.1	%	N/A
Sb	2.9	0.1	ppm	0.1
Sc	34.6	0.4	ppm	0.1
Se	3.0	0.9	ppm	2.8
Si	9.7	1.0	%	2.3
Sm	19.0	0.2	ppm	0.1
Sr	407	36.3	ppm	90
Ta	0.80	0.04	ppm	0.11
Th	11.5	0.2	ppm	0.5
Ti	3590	190	ppm	200
U	6.0	0.3	ppm	0.8
V	232	5	ppm	3
Zn	79	12	ppm	N/A
Zr	94	14	ppm	N/A

Table C6. Rock Island fly ash.

Element	Conc.	±	Unit	Detection Limit
Ag	0	0	ppm	1
Al	10.3	0.7	%	0.1
As	31.5	0.6	ppm	1.5
Ba	435	39	ppm	70
Br	5.4	1.6	ppm	5.1
Ca	0.63	0.03	%	0.02

Element	Conc.	±	Unit	Detection Limit
Ce	105	2	ppm	4
Cl	65.1	7.4	ppm	20.0
Co	56.2	0.8	ppm	0.1
Cr	167.1	3.5	ppm	8.0
Cs	4.4	0.1	ppm	0.3
Cu	74	11	ppm	N/A
Dy	16.6	1.3	ppm	0.4
Fe	3.6	0.1	%	0.1
Hg	0	0	ppm	1
In	42.2	10.7	ppb	33.0
I	0	0	ppm	2
K	0.8	0.1	%	0.2
La	63.0	0.8	ppm	0.2
Mn	64.0	3.0	ppm	1.3
Mo	16.0	2.4	ppm	N/A
Na	1170	70	ppm	50
Ni	73	11	ppm	N/A
Pb	41.0	6.2	ppm	N/A
Rb	53.6	6.7	ppm	21.6
S	0.6	0.1	%	N/A
Sb	5.6	0.1	ppm	0.1
Sc	34.6	0.4	ppm	0.1
Se	9.5	0.9	ppm	2.9
Si	14.8	1.4	%	3.3
Sm	16.8	0.2	ppm	0.1
Sr	470	40	ppm	100
Ta	1.06	0.04	ppm	0.11
Th	19.0	0.3	ppm	0.6
Ti	4680	250	ppm	270
U	12.3	0.4	ppm	0.9
V	340.2	7.5	ppm	3.8
Zn	44.0	6.6	ppm	N/A
Zr	126	19	ppm	N/A

## Appendix D: Elemental Concentrations in Water Batch Extractions

This appendix lists the concentrations of elements in the water batch extraction samples of bottom ash and fly ash. All leachate sample concentrations were determined by inductively coupled plasma analysis.

Table D1 lists the bottom ash elements for which concentrations were at or below detection limits for all liquid-to-solid ratios (2-50). Table D2 lists the identification codes for the bottom ash leachate samples. Concentration levels are arranged in groups of two elements each in Tables D3 through D10.

Table D11 lists the fly ash elements for which concentrations were at or below detection limits for all liquid-to-solid ratios (2-50). Table D12 lists the identification codes for the fly ash leachate samples. Concentration levels are arranged in groups of two elements each in Tables D13 through D21.

**Table D1. Bottom ash elements at or below detection limits for all liquid-to-solid ratios (2-50).**

Element	Detection Limit	Unit
Ag	<0.014	ppm
As	<0.183	ppm
Be	<0.003	ppm
Cd	<0.014	ppm
Co	<0.021	ppm
Cu	<0.009	ppm
Hg	<0.066	ppm
Mn	<0.004	ppm
Ni	<0.040	ppm
P	<0.412	ppm
Pb	<0.088	ppm

**Table D1. Bottom ash elements at or below detection limits for all liquid-to-solid ratios (2-50).**

Element	Detection Limit	Unit
Sb	<0.500	ppm
Se	<0.250	ppm
Sn	<0.110	ppm
Ti	<0.004	ppm
Tl	<0.340	ppm

**Table D2. Bottom ash sample identification codes.**

Sample ID codes	Meaning
AB	Abbott bottom ash
CB	Chanute bottom ash
RB	Rock Island bottom ash
LS	Liquid-to-solid ratio

**Table D3. Elemental concentrations of Al (MDL = 0.036) and B (MDL= 0.039) in bottom ash leachate.**

Sample ID	LS	Al $\pm 0.094$	B $\pm 0.039$	Unit
AB	2	<0.036	<0.039	ppm
AB	4	<0.036	<0.039	ppm
AB	6	<0.036	<0.039	ppm
AB	8	0.95	<0.039	ppm
AB	10	1.24	<0.039	ppm
AB	14	1.99	0.25	ppm
AB	18	1.98	0.34	ppm
AB	22	1.84	0.29	ppm
AB	26	1.52	0.16	ppm
AB	30	1.46	0.12	ppm
AB	34	1.30	0.12	ppm
AB	38	1.26	0.13	ppm
AB	42	1.16	<0.039	ppm
AB	46	1.11	<0.039	ppm



Sample ID	LS	AI $\pm 0.094$	B $\pm 0.039$	Unit
AB	50	1.03	<0.039	ppm
CB	2	3.32	3.50	ppm
CB	4	1.51	2.14	ppm
CB	6	0.585	1.33	ppm
CB	8	0.666	0.51	ppm
CB	10	0.475	0.42	ppm
CB	14	0.847	0.11	ppm
CB	18	0.872	<0.039	ppm
CB	22	0.963	<0.039	ppm
CB	26	1.02	<0.039	ppm
CB	30	1.03	<0.039	ppm
CB	34	0.978	<0.039	ppm
CB	38	1.00	<0.039	ppm
CB	42	1.05	<0.039	ppm
CB	46	1.02	<0.039	ppm
CB	50	1.00	<0.039	ppm
RB	2	0.559	2.30	ppm
RB	4	0.625	0.68	ppm
RB	6	0.692	0.35	ppm
RB	8	0.788	0.08	ppm
RB	10	0.438	<0.039	ppm
RB	14	0.875	<0.039	ppm
RB	18	0.855	<0.039	ppm
RB	22	0.923	<0.039	ppm
RB	26	1.08	<0.039	ppm
RB	30	1.07	<0.039	ppm
RB	34	0.445	<0.039	ppm
RB	38	1.03	<0.039	ppm
RB	42	1.15	<0.039	ppm
RB	46	1.08	<0.039	ppm
RB	50	1.12	<0.039	ppm

**Table D4. Elemental concentrations of Ba (MDL = 0.009) and Ca (MD = 0.073) in bottom ash leachate.**

Sample ID	LS	Ba $\pm 0.009$	Ca $\pm 3.10$	Unit
AB	2	0.393	997	ppm
AB	4	0.301	549	ppm
AB	6	0.195	234	ppm
AB	8	0.082	127	ppm
AB	10	0.067	117	ppm
AB	14	0.035	76.0	ppm
AB	18	0.027	61.1	ppm
AB	22	0.024	54.1	ppm
AB	26	0.018	49.8	ppm
AB	30	0.019	48.3	ppm
AB	34	0.019	51.1	ppm
AB	38	0.016	53.9	ppm
AB	42	0.015	42.0	ppm
AB	46	0.018	40.6	ppm
AB	50	0.016	42.8	ppm
CB	2	0.049	127	ppm
CB	4	0.017	64.9	ppm
CB	6	0.025	53.1	ppm
CB	8	0.013	33.4	ppm
CB	10	0.021	27.6	ppm
CB	14	<0.009	15.1	ppm
CB	18	0.025	11.2	ppm
CB	22	0.033	10.1	ppm
CB	26	0.027	9.48	ppm
CB	30	0.025	9.03	ppm
CB	34	0.018	8.70	ppm
CB	38	0.015	8.79	ppm
CB	42	0.015	7.44	ppm
CB	46	0.033	7.29	ppm
CB	50	0.039	7.46	ppm
RB	2	0.042	57.5	ppm

Sample ID	LS	Ba $\pm 0.009$	Ca $\pm 3.10$	Unit
RB	4	0.022	22.3	ppm
RB	6	0.044	14.7	ppm
RB	8	0.050	11.4	ppm
RB	10	0.077	10.8	ppm
RB	14	0.039	8.52	ppm
RB	18	0.048	7.83	ppm
RB	22	0.035	7.52	ppm
RB	26	0.036	7.02	ppm
RB	30	0.024	7.13	ppm
RB	34	0.029	6.75	ppm
RB	38	0.022	7.32	ppm
RB	42	0.017	6.63	ppm
RB	46	0.030	6.56	ppm
RB	50	0.030	6.96	ppm

**Table D5. Elemental concentrations of Cr (MDL = 0.011) and Fe (MDL = 0.015) in bottom ash leachate.**

Sample ID	LS	Cr $\pm 0.011$	Fe $\pm 0.015$	Unit
AB	2	0.050	<0.015	ppm
AB	4	0.046	<0.015	ppm
AB	6	0.033	<0.015	ppm
AB	8	0.033	<0.015	ppm
AB	10	0.029	<0.015	ppm
AB	14	0.023	<0.015	ppm
AB	18	0.025	<0.015	ppm
AB	22	0.021	<0.015	ppm
AB	26	0.013	<0.015	ppm
AB	30	0.016	<0.015	ppm
AB	34	0.014	<0.015	ppm
AB	38	<0.011	<0.015	ppm
AB	42	0.012	<0.015	ppm
AB	46	0.012	<0.015	ppm

Sample ID	LS	Cr $\pm 0.011$	Fe $\pm 0.015$	Unit
AB	50	<0.011	<0.015	ppm
CB	2	0.016	<0.015	ppm
CB	4	0.015	<0.015	ppm
CB	6	<0.011	<0.015	ppm
CB	8	<0.011	<0.015	ppm
CB	10	<0.011	<0.015	ppm
CB	14	<0.011	<0.015	ppm
CB	18	<0.011	<0.015	ppm
CB	22	<0.011	<0.015	ppm
CB	26	<0.011	<0.015	ppm
CB	30	<0.011	<0.015	ppm
CB	34	<0.011	<0.015	ppm
CB	38	<0.011	<0.015	ppm
CB	42	<0.011	<0.015	ppm
CB	46	<0.011	<0.015	ppm
CB	50	<0.011	<0.015	ppm
RB	2	0.013	<0.015	ppm
RB	4	<0.011	<0.015	ppm
RB	6	0.012	<0.015	ppm
RB	8	<0.011	<0.015	ppm
RB	10	<0.011	<0.015	ppm
RB	14	<0.011	<0.015	ppm
RB	18	<0.011	<0.015	ppm
RB	22	<0.011	<0.015	ppm
RB	26	<0.011	<0.015	ppm
RB	30	<0.011	<0.015	ppm
RB	34	<0.011	<0.015	ppm
RB	38	<0.011	0.017	ppm
RB	42	<0.011	0.036	ppm
RB	46	<0.011	0.020	ppm
RB	50	<0.011	0.025	ppm

**Table D6. Elemental concentrations of K (MDL = 2.254) and Li (MDL= 0.003) in bottom ash leachate.**

Sample ID	LS	K $\pm 0.762$	Li $\pm 0.003$	Unit
AB	2	24.2	0.038	ppm
AB	6	6.51	0.030	ppm
AB	8	2.28	0.018	ppm
AB	10	2.68	0.015	ppm
AB	14	<2.254	0.007	ppm
AB	18	<2.254	0.005	ppm
AB	22	<2.254	0.003	ppm
AB	26	<2.254	<0.003	ppm
AB	30	<2.254	<0.003	ppm
AB	34	<2.254	<0.003	ppm
AB	38	<2.254	<0.003	ppm
AB	42	<2.254	<0.003	ppm
AB	46	<2.254	<0.003	ppm
AB	50	<2.254	<0.003	ppm
CB	2	9.60	1.10	ppm
CB	4	4.40	0.489	ppm
CB	6	3.22	0.311	ppm
CB	8	<2.254	0.152	ppm
CB	10	<2.254	0.126	ppm
CB	14	<2.254	0.059	ppm
CB	18	<2.254	0.037	ppm
CB	22	<2.254	0.031	ppm
CB	26	<2.254	0.028	ppm
CB	30	<2.254	0.024	ppm
CB	34	<2.254	0.020	ppm
CB	38	<2.254	0.026	ppm
CB	42	<2.254	0.017	ppm
CB	46	<2.254	0.015	ppm
CB	50	<2.254	0.017	ppm
RB	2	10.1	0.669	ppm
RB	4	4.71	0.342	ppm

Sample ID	LS	K $\pm 0.762$	Li $\pm 0.003$	Unit
RB	6	4.23	0.270	ppm
RB	8	<2.254	0.160	ppm
RB	10	<2.254	0.122	ppm
RB	14	<2.254	0.056	ppm
RB	18	<2.254	0.038	ppm
RB	22	<2.254	0.030	ppm
RB	26	<2.254	0.022	ppm
RB	30	<2.254	0.022	ppm
RB	34	<2.254	0.021	ppm
RB	38	<2.254	0.026	ppm
RB	42	<2.254	0.017	ppm
RB	46	<2.254	0.014	ppm
RB	50	<2.254	0.015	ppm

**Table D7. Elemental concentrations of Mg (MDL = 0.006) and Mo (MDL= 0.016) in bottom ash leachate.**

Sample ID	LS	Mg $\pm 0.006$	Mo $\pm 0.016$	Unit
AB	2	0.016	0.569	ppm
AB	4	0.013	0.264	ppm
AB	6	0.021	0.163	ppm
AB	8	0.038	0.049	ppm
AB	10	0.063	0.049	ppm
AB	14	0.067	<0.016	ppm
AB	18	0.074	<0.016	ppm
AB	22	0.078	<0.016	ppm
AB	26	0.078	<0.016	ppm
AB	30	0.087	<0.016	ppm
AB	34	0.091	<0.016	ppm
AB	38	0.105	<0.016	ppm
AB	42	0.103	<0.016	ppm
AB	46	0.107	<0.016	ppm
AB	50	0.115	<0.016	ppm

Sample ID	LS	Mg $\pm 0.006$	Mo $\pm 0.016$	Unit
CB	2	0.052	0.200	ppm
CB	4	0.146	0.054	ppm
CB	6	0.313	<0.016	ppm
CB	8	0.302	<0.016	ppm
CB	10	0.504	<0.016	ppm
CB	14	0.388	<0.016	ppm
CB	18	0.366	<0.016	ppm
CB	22	0.403	<0.016	ppm
CB	26	0.440	<0.016	ppm
CB	30	0.486	<0.016	ppm
CB	34	0.559	<0.016	ppm
CB	38	0.631	<0.016	ppm
CB	42	0.495	<0.016	ppm
CB	46	0.462	<0.016	ppm
CB	50	0.484	<0.016	ppm
RB	2	0.774	0.687	ppm
RB	4	0.693	0.146	ppm
RB	6	0.869	0.080	ppm
RB	8	0.714	<0.016	ppm
RB	10	0.751	<0.016	ppm
RB	14	0.498	<0.016	ppm
RB	18	0.421	<0.016	ppm
RB	22	0.368	<0.016	ppm
RB	26	0.311	<0.016	ppm
RB	30	0.300	<0.016	ppm
RB	34	0.284	0.031	ppm
RB	38	0.314	<0.016	ppm
RB	42	0.250	<0.016	ppm
RB	46	0.226	<0.016	ppm
RB	50	0.236	0.021	ppm

**Table D8. Elemental concentrations of Na (MDL = 0.052) and S (MDL= 0.24) in bottom ash leachate.**

Sample ID	LS	Na $\pm 0.052$	S $\pm 0.24$	Unit
AB	2	28.5	229	ppm
AB	4	8.89	57.6	ppm
AB	6	5.52	54.3	ppm
AB	8	2.52	36.3	ppm
AB	10	2.18	49.8	ppm
AB	14	0.888	23.2	ppm
AB	18	0.536	14.2	ppm
AB	22	0.396	10.8	ppm
AB	26	0.354	8.46	ppm
AB	30	0.320	7.98	ppm
AB	34	0.372	9.43	ppm
AB	38	0.463	11.4	ppm
AB	42	0.321	6.93	ppm
AB	46	0.278	5.48	ppm
AB	50	0.301	5.85	ppm
CB	2	7.43	56.7	ppm
CB	4	3.10	26.1	ppm
CB	6	2.19	20.7	ppm
CB	8	1.04	8.36	ppm
CB	10	0.937	9.08	ppm
CB	14	0.421	3.00	ppm
CB	18	0.332	1.49	ppm
CB	22	0.324	1.66	ppm
CB	26	0.290	1.55	ppm
CB	30	0.276	1.35	ppm
CB	34	0.366	1.54	ppm
CB	38	0.245	1.98	ppm
CB	42	0.236	1.06	ppm
CB	46	0.291	0.99	ppm
CB	50	0.300	1.27	ppm
RB	2	2.09	33.5	ppm



Sample ID	LS	Na $\pm 0.052$	S $\pm 0.24$	Unit
RB	4	1.06	9.12	ppm
RB	6	0.982	5.16	ppm
RB	8	0.696	2.25	ppm
RB	10	0.736	2.06	ppm
RB	14	0.363	0.74	ppm
RB	18	0.339	0.64	ppm
RB	22	0.277	0.47	ppm
RB	26	0.234	0.38	ppm
RB	30	0.194	0.56	ppm
RB	34	0.233	0.62	ppm
RB	38	0.171	0.86	ppm
RB	42	0.148	0.56	ppm
RB	46	0.191	0.47	ppm
RB	50	0.171	0.58	ppm

**Table D9. Elemental concentrations of Si (MDL = 0.040) and Sr (MDL= 0.002) in bottom ash leachate.**

Sample ID	LS	Si $\pm 0.04$	Sr $\pm 0.002$	Unit
AB	2	0.46	3.36	ppm
AB	4	0.90	1.42	ppm
AB	6	3.23	0.578	ppm
AB	8	5.96	0.266	ppm
AB	10	6.31	0.205	ppm
AB	14	6.14	0.113	ppm
AB	18	6.59	0.089	ppm
AB	22	6.92	0.078	ppm
AB	26	8.16	0.081	ppm
AB	30	8.43	0.078	ppm
AB	34	8.66	0.081	ppm
AB	38	9.04	0.085	ppm
AB	42	8.87	0.065	ppm
AB	46	9.63	0.068	ppm

Sample ID	LS	Si $\pm 0.04$	Sr $\pm 0.002$	Unit
AB	50	10.0	0.071	ppm
CB	2	8.53	0.762	ppm
CB	4	11.0	0.351	ppm
CB	6	14.1	0.279	ppm
CB	8	11.6	0.167	ppm
CB	10	7.97	0.129	ppm
CB	14	4.47	0.076	ppm
CB	18	3.24	0.062	ppm
CB	22	2.89	0.052	ppm
CB	26	2.81	0.051	ppm
CB	30	2.55	0.051	ppm
CB	34	2.39	0.049	ppm
CB	38	2.47	0.051	ppm
CB	42	2.18	0.042	ppm
CB	46	2.12	0.042	ppm
CB	50	2.21	0.043	ppm
RB	2	6.34	0.355	ppm
RB	4	3.88	0.127	ppm
RB	6	3.07	0.090	ppm
RB	8	2.76	0.066	ppm
RB	10	2.44	0.060	ppm
RB	14	2.34	0.045	ppm
RB	18	2.21	0.040	ppm
RB	22	2.05	0.039	ppm
RB	26	2.05	0.035	ppm
RB	30	2.06	0.035	ppm
RB	34	1.84	0.031	ppm
RB	38	2.18	0.037	ppm
RB	42	2.06	0.030	ppm
RB	46	1.91	0.030	ppm
RB	50	1.99	0.030	ppm

**Table D10. Elemental concentrations of V (MDL = 0.009) and Zn (MDL= 0.012) in bottom ash leachate.**

Sample ID	LS	V $\pm 0.009$	Zn $\pm 0.012$	Unit
AB	2	<0.009	0.546	ppm
AB	6	0.024	<0.012	ppm
AB	8	0.048	<0.012	ppm
AB	10	0.064	0.015	ppm
AB	14	0.062	<0.012	ppm
AB	18	0.062	<0.012	ppm
AB	22	0.051	<0.012	ppm
AB	26	0.051	<0.012	ppm
AB	30	0.046	<0.012	ppm
AB	34	0.042	<0.012	ppm
AB	38	0.042	<0.012	ppm
AB	42	0.029	<0.012	ppm
AB	46	0.029	<0.012	ppm
AB	50	0.029	<0.012	ppm
CB	2	0.320	<0.012	ppm
CB	4	0.330	<0.012	ppm
CB	6	0.283	<0.012	ppm
CB	8	0.146	<0.012	ppm
CB	10	0.110	<0.012	ppm
CB	14	0.049	<0.012	ppm
CB	18	0.037	<0.012	ppm
CB	22	0.037	0.021	ppm
CB	26	0.033	<0.012	ppm
CB	30	0.022	<0.012	ppm
CB	34	0.020	0.020	ppm
CB	38	0.033	<0.012	ppm
CB	42	0.013	<0.012	ppm
CB	46	0.009	0.020	ppm
CB	50	0.011	0.022	ppm
RB	2	1.08	<0.012	ppm
RB	4	0.430	<0.012	ppm

Sample ID	LS	V $\pm 0.009$	Zn $\pm 0.012$	Unit
RB	6	0.242	<0.012	ppm
RB	8	0.138	0.017	ppm
RB	10	0.103	0.036	ppm
RB	14	0.055	0.027	ppm
RB	18	0.031	0.028	ppm
RB	22	0.029	<0.012	ppm
RB	26	0.033	0.017	ppm
RB	30	0.026	<0.012	ppm
RB	34	0.042	<0.012	ppm
RB	38	0.037	<0.012	ppm
RB	42	0.024	<0.012	ppm
RB	46	0.022	0.017	ppm
RB	50	0.033	<0.012	ppm

**Table D11. Fly ash elements at or below detection limits for all liquid-to-solid ratios (2-50).**

Element	Detection Limit	Unit
Ag	<0.008	ppm
As	<0.280	ppm
Be	<0.002	ppm
Cd	<0.024	ppm
Co	<0.009	ppm
Cr	<0.018	ppm
Cu	<0.006	ppm
Fe	<0.003	ppm
Hg	<0.040	ppm
Pb	<0.051	ppm
Sb	<0.270	ppm
Se	<0.490	ppm
Sn	<0.041	ppm
Ti	<0.003	ppm
Tl	<0.350	ppm

**Table D12. Fly ash sample identification codes.**

Sample ID codes	Meaning
AF/C	Abbott fly/bottom ash
CF	Chanute fly ash
RF	Rock Island fly ash
LS	liquid-to-solid ratio

**Table D13. Elemental concentrations of Al (MDL = 0.024) and B (MDL = 0.030) in fly ash leachate.**

Sample ID	LS	Al $\pm 0.024$	B $\pm 0.030$	Unit
AF/C	2	0.174	19.9	ppm
AF/C	4	0.127	9.84	ppm
AF/C	6	0.154	5.98	ppm
AF/C	8	0.239	4.32	ppm
AF/C	10	0.209	3.41	ppm
AF/C	14	0.244	2.21	ppm
AF/C	18	0.291	1.58	ppm
AF/C	22	0.508	1.33	ppm
AF/C	26	0.698	1.21	ppm
AF/C	30	0.708	1.12	ppm
AF/C	34	0.837	0.84	ppm
AF/C	38	0.709	0.50	ppm
AF/C	42	0.562	0.52	ppm
AF/C	46	0.480	0.68	ppm
AF/C	50	0.562	0.73	ppm
CF	2	0.127	1.26	ppm
CF	4	2.58	4.21	ppm
CF	6	1.84	3.25	ppm
CF	8	1.50	2.37	ppm
CF	10	1.72	2.20	ppm
CF	14	3.44	1.90	ppm

Sample ID	LS	Al $\pm 0.024$	B $\pm 0.030$	Unit
CF	18	4.40	1.64	ppm
CF	22	4.00	1.29	ppm
CF	26	3.11	0.96	ppm
CF	30	2.17	0.77	ppm
CF	34	1.74	0.58	ppm
CF	38	1.62	0.37	ppm
CF	42	1.56	0.27	ppm
CF	46	1.43	0.28	ppm
CF	50	1.30	0.27	ppm
RF	2	0.407	16.50	ppm
RF	4	0.072	7.09	ppm
RF	6	0.051	3.56	ppm
RF	8	0.062	2.25	ppm
RF	10	<0.024	1.42	ppm
RF	14	0.063	0.73	ppm
RF	18	<0.024	0.44	ppm
RF	22	0.042	0.26	ppm
RF	26	0.050	0.22	ppm
RF	30	0.038	0.23	ppm
RF	34	0.050	0.17	ppm
RF	38	<0.024	0.07	ppm
RF	42	<0.024	<0.03	ppm
RF	46	0.045	0.07	ppm
RF	50	<0.024	0.07	ppm

**Table D14. Elemental concentrations of Ba (MDL = 0.002) and Ca (MDL = 0.040) in fly ash leachate.**

Sample ID	LS	Ba $\pm 0.009$	Ca $\pm 0.040$	Unit
AF/C	2	0.075	460	ppm
AF/C	4	0.059	525	ppm
AF/C	6	0.052	563	ppm
AF/C	8	0.050	586	ppm

Sample ID	LS	Ba $\pm 0.009$	Ca $\pm 0.040$	Unit
AF/C	10	0.045	581	ppm
AF/C	14	0.038	486	ppm
AF/C	18	0.022	117	ppm
AF/C	22	0.021	40.9	ppm
AF/C	26	0.014	21.3	ppm
AF/C	30	0.015	16.5	ppm
AF/C	34	0.019	14.3	ppm
AF/C	38	0.036	12.0	ppm
AF/C	42	0.058	12.0	ppm
AF/C	46	0.081	12.8	ppm
AF/C	50	0.080	13.3	ppm
CF	2	0.134	354	ppm
CF	4	0.045	129	ppm
CF	6	0.034	78.9	ppm
CF	8	0.036	56.3	ppm
CF	10	0.020	49.0	ppm
CF	14	0.018	42.4	ppm
CF	18	0.017	38.4	ppm
CF	22	0.016	32.4	ppm
CF	26	0.015	26.1	ppm
CF	30	0.014	23.4	ppm
CF	34	0.009	19.1	ppm
CF	38	0.009	13.4	ppm
CF	42	0.017	12.2	ppm
CF	46	0.010	14.4	ppm
CF	50	0.016	14.5	ppm
RF	2	0.132	416	ppm
RF	4	0.102	129	ppm
RF	6	0.106	49.5	ppm
RF	8	0.124	22.8	ppm
RF	10	0.097	12.0	ppm
RF	14	0.102	5.37	ppm

Sample ID	LS	Ba $\pm 0.009$	Ca $\pm 0.040$	Unit
RF	18	0.097	3.27	ppm
RF	22	0.091	2.45	ppm
RF	26	0.081	2.17	ppm
RF	30	0.086	2.37	ppm
RF	34	0.072	2.07	ppm
RF	38	0.051	1.51	ppm
RF	42	0.048	1.27	ppm
RF	46	0.056	1.45	ppm
RF	50	0.060	1.50	ppm

**Table D15. Elemental concentrations of K (MDL = 1.93) and Li (MDL = 0.003) in fly ash leachate.**

Sample ID	LS	K $\pm 1.93$	Li $\pm 0.003$	Unit
AF/C	2	366	0.605	ppm
AF/C	4	130	0.266	ppm
AF/C	6	60.9	0.147	ppm
AF/C	8	36.1	0.098	ppm
AF/C	10	22.9	0.068	ppm
AF/C	14	12.7	0.039	ppm
AF/C	18	8.58	0.023	ppm
AF/C	22	5.84	0.014	ppm
AF/C	26	4.70	0.014	ppm
AF/C	30	4.18	0.013	ppm
AF/C	34	4.46	0.013	ppm
AF/C	38	3.87	0.010	ppm
AF/C	42	3.22	0.011	ppm
AF/C	46	3.87	0.011	ppm
AF/C	50	3.80	0.012	ppm
CF	2	5.24	0.236	ppm
CF	4	2.31	0.098	ppm
CF	6	3.74	0.098	ppm
CF	8	4.25	0.101	ppm



Sample ID	LS	K $\pm 1.93$	Li $\pm 0.003$	Unit
CF	10	2.28	0.108	ppm
CF	14	2.38	0.081	ppm
CF	18	2.11	0.066	ppm
CF	22	<1.93	0.056	ppm
CF	26	2.25	0.057	ppm
CF	30	2.31	0.062	ppm
CF	34	2.21	0.057	ppm
CF	38	<1.93	0.038	ppm
CF	42	<1.93	0.030	ppm
CF	46	<1.93	0.035	ppm
CF	50	<1.93	0.037	ppm
RF	2	115	6.30	ppm
RF	4	40.3	1.88	ppm
RF	6	19.3	0.712	ppm
RF	8	8.54	0.341	ppm
RF	10	4.81	0.160	ppm
RF	14	2.88	0.064	ppm
RF	18	<1.93	0.036	ppm
RF	22	<1.93	0.024	ppm
RF	26	<1.93	0.020	ppm
RF	30	<1.93	0.018	ppm
RF	34	<1.93	0.016	ppm
RF	38	<1.93	0.010	ppm
RF	42	<1.93	0.009	ppm
RF	46	<1.93	0.009	ppm
RF	50	<1.93	0.010	ppm

**Table D16. Elemental concentrations of Mg (MDL = 0.002) and Mn (MDL = 0.005) in fly ash leachate.**

Sample ID	LS	Mg $\pm 0.002$	Mn $\pm 0.005$	Unit
AF/C	2	10.1	0.011	ppm
AF/C	4	6.49	0.006	ppm
AF/C	6	4.57	<0.005	ppm
AF/C	8	3.58	<0.005	ppm
AF/C	10	3.35	<0.005	ppm
AF/C	14	1.74	<0.005	ppm
AF/C	18	0.584	<0.005	ppm
AF/C	22	0.280	<0.005	ppm
AF/C	26	0.182	<0.005	ppm
AF/C	30	0.188	<0.005	ppm
AF/C	34	0.181	<0.005	ppm
AF/C	38	0.157	<0.005	ppm
AF/C	42	0.158	<0.005	ppm
AF/C	46	0.184	<0.005	ppm
AF/C	50	0.200	<0.005	ppm
CF	2	0.005	<0.005	ppm
CF	4	0.052	<0.005	ppm
CF	6	0.094	<0.005	ppm
CF	8	0.154	<0.005	ppm
CF	10	0.291	<0.005	ppm
CF	14	0.322	<0.005	ppm
CF	18	0.335	<0.005	ppm
CF	22	0.332	<0.005	ppm
CF	26	0.359	<0.005	ppm
CF	30	0.469	<0.005	ppm
CF	34	0.431	<0.005	ppm
CF	38	0.301	<0.005	ppm
CF	42	0.266	<0.005	ppm
CF	46	0.334	<0.005	ppm
CF	50	0.353	<0.005	ppm
RF	2	26.8	2.62	ppm

Sample ID	LS	Mg $\pm 0.002$	Mn $\pm 0.005$	Unit
RF	4	8.66	0.810	ppm
RF	6	3.43	0.312	ppm
RF	8	1.64	0.155	ppm
RF	10	0.949	0.082	ppm
RF	14	0.448	0.035	ppm
RF	18	0.280	0.018	ppm
RF	22	0.222	0.012	ppm
RF	26	0.206	0.012	ppm
RF	30	0.245	0.012	ppm
RF	34	0.218	0.011	ppm
RF	38	0.154	0.005	ppm
RF	42	0.124	<0.005	ppm
RF	46	0.148	0.006	ppm
RF	50	0.158	<0.005	ppm

**Table D17. Elemental concentrations of Mo (MDL = 0.090) and Na (MDL = 0.019) in fly ash leachate.**

Sample ID	LS	Mo $\pm 0.090$	Na $\pm 0.019$	Unit
AF/C	2	1.360	720	ppm
AF/C	4	0.470	208	ppm
AF/C	6	0.210	76.1	ppm
AF/C	8	0.180	33.1	ppm
AF/C	10	0.140	18.4	ppm
AF/C	14	<0.090	8.45	ppm
AF/C	18	<0.090	3.97	ppm
AF/C	22	<0.090	2.63	ppm
AF/C	26	<0.090	2.26	ppm
AF/C	30	<0.090	2.36	ppm
AF/C	34	<0.090	2.10	ppm
AF/C	38	<0.090	1.58	ppm
AF/C	42	<0.090	1.64	ppm
AF/C	46	<0.090	2.03	ppm

Sample ID	LS	Mo $\pm 0.090$	Na $\pm 0.019$	Unit
AF/C	50	<0.090	2.19	ppm
CF	2	0.440	6.42	ppm
CF	4	0.340	2.12	ppm
CF	6	0.110	2.02	ppm
CF	8	<0.090	1.94	ppm
CF	10	<0.090	1.90	ppm
CF	14	<0.090	1.26	ppm
CF	18	<0.090	0.953	ppm
CF	22	<0.090	0.794	ppm
CF	26	<0.090	0.712	ppm
CF	30	<0.090	0.742	ppm
CF	34	<0.090	0.619	ppm
CF	38	<0.090	0.413	ppm
CF	42	<0.090	0.332	ppm
CF	46	<0.090	0.369	ppm
CF	50	<0.090	0.386	ppm
RF	2	<0.090	47.1	ppm
RF	4	<0.090	14.5	ppm
RF	6	<0.090	5.71	ppm
RF	8	<0.090	2.92	ppm
RF	10	<0.090	1.53	ppm
RF	14	<0.090	0.705	ppm
RF	18	<0.090	0.459	ppm
RF	22	<0.090	0.310	ppm
RF	26	<0.090	0.266	ppm
RF	30	<0.090	0.292	ppm
RF	34	<0.090	0.233	ppm
RF	38	<0.090	0.171	ppm
RF	42	<0.090	0.144	ppm
RF	46	<0.090	0.168	ppm
RF	50	<0.090	0.178	ppm

**Table D18. Elemental concentrations of Ni (MDL = 0.039) and P (MDL = 0.090) in fly ash leachate.**

Sample ID	LS	Ni $\pm 0.039$	P $\pm 0.090$	Unit
AF/C	2	<0.039	<0.090	ppm
AF/C	4	<0.039	<0.090	ppm
AF/C	6	<0.039	<0.090	ppm
AF/C	8	<0.039	<0.090	ppm
AF/C	10	<0.039	<0.090	ppm
AF/C	14	<0.039	<0.090	ppm
AF/C	18	<0.039	<0.090	ppm
AF/C	22	<0.039	<0.090	ppm
AF/C	26	<0.039	<0.090	ppm
AF/C	30	<0.039	<0.090	ppm
AF/C	34	<0.039	<0.090	ppm
AF/C	38	<0.039	<0.090	ppm
AF/C	42	<0.039	<0.090	ppm
AF/C	46	<0.039	<0.090	ppm
AF/C	50	<0.039	<0.090	ppm
CF	2	<0.039	<0.090	ppm
CF	4	<0.039	0.180	ppm
CF	6	<0.039	0.110	ppm
CF	8	<0.039	<0.090	ppm
CF	10	<0.039	0.170	ppm
CF	14	<0.039	0.150	ppm
CF	18	<0.039	0.140	ppm
CF	22	<0.039	0.160	ppm
CF	26	<0.039	0.530	ppm
CF	30	<0.039	0.490	ppm
CF	34	<0.039	0.200	ppm
CF	38	<0.039	0.590	ppm
CF	42	<0.039	0.680	ppm
CF	46	<0.039	0.390	ppm
CF	50	<0.039	0.770	ppm
RF	2	0.331	0.100	ppm

Sample ID	LS	Ni $\pm 0.039$	P $\pm 0.090$	Unit
RF	4	0.139	<0.090	ppm
RF	6	0.045	0.180	ppm
RF	8	<0.039	<0.090	ppm
RF	10	<0.039	<0.090	ppm
RF	14	<0.039	<0.090	ppm
RF	18	<0.039	0.140	ppm
RF	22	<0.039	0.200	ppm
RF	26	<0.039	0.230	ppm
RF	30	<0.039	<0.090	ppm
RF	34	<0.039	0.180	ppm
RF	38	<0.039	<0.090	ppm
RF	42	<0.039	0.180	ppm
RF	46	<0.039	0.200	ppm
RF	50	<0.039	<0.090	ppm

**Table D19. Elemental concentrations of S (MDL = 0.090) and Si (MDL = 0.030) in fly ash leachate.**

Sample ID	LS	S $\pm 0.090$	Si $\pm 0.030$	Unit
AF/C	2	1009	2.19	ppm
AF/C	4	612	2.03	ppm
AF/C	6	524	2.15	ppm
AF/C	8	497	2.37	ppm
AF/C	10	486	2.19	ppm
AF/C	14	393	2.82	ppm
AF/C	18	90.2	3.16	ppm
AF/C	22	28.2	3.37	ppm
AF/C	26	11.2	3.91	ppm
AF/C	30	6.54	3.87	ppm
AF/C	34	3.99	3.91	ppm
AF/C	38	2.01	3.76	ppm
AF/C	42	2.36	3.66	ppm
AF/C	46	3.14	4.02	ppm

Sample ID	LS	S $\pm 0.090$	Si $\pm 0.030$	Unit
AF/C	50	3.57	4.03	ppm
CF	2	108	2.89	ppm
CF	4	66.9	5.58	ppm
CF	6	34.5	6.49	ppm
CF	8	23.7	5.95	ppm
CF	10	21.1	3.64	ppm
CF	14	16.8	1.80	ppm
CF	18	14.0	1.42	ppm
CF	22	11.4	1.29	ppm
CF	26	8.61	1.46	ppm
CF	30	7.78	1.55	ppm
CF	34	5.96	1.80	ppm
CF	38	3.34	1.90	ppm
CF	42	2.35	2.00	ppm
CF	46	3.33	2.26	ppm
CF	50	3.56	2.46	ppm
RF	2	470	22.4	ppm
RF	4	145	11.8	ppm
RF	6	56.3	7.63	ppm
RF	8	27.3	6.70	ppm
RF	10	13.8	6.31	ppm
RF	14	5.60	5.44	ppm
RF	18	3.33	4.82	ppm
RF	22	1.88	4.44	ppm
RF	26	1.71	4.66	ppm
RF	30	1.56	5.27	ppm
RF	34	1.27	4.92	ppm
RF	38	0.74	3.32	ppm
RF	42	0.54	2.72	ppm
RF	46	0.58	3.55	ppm
RF	50	0.77	3.83	ppm

**Table D20. Elemental concentrations of Sr (MDL = 0.003) and V (MDL = 0.009) in fly ash leachate.**

Sample ID	LS	Sr $\pm 0.003$	V $\pm 0.009$	Unit
AF/C	2	0.973	<0.009	ppm
AF/C	4	0.872	<0.009	ppm
AF/C	6	0.810	0.013	ppm
AF/C	8	0.768	0.019	ppm
AF/C	10	0.720	0.010	ppm
AF/C	14	0.592	0.015	ppm
AF/C	18	0.176	0.019	ppm
AF/C	22	0.069	0.023	ppm
AF/C	26	0.041	0.032	ppm
AF/C	30	0.031	0.036	ppm
AF/C	34	0.028	0.038	ppm
AF/C	38	0.024	0.030	ppm
AF/C	42	0.025	0.036	ppm
AF/C	46	0.028	0.038	ppm
AF/C	50	0.029	0.032	ppm
CF	2	1.30	0.019	ppm
CF	4	0.585	0.175	ppm
CF	6	0.364	0.223	ppm
CF	8	0.273	0.218	ppm
CF	10	0.239	0.190	ppm
CF	14	0.200	0.116	ppm
CF	18	0.175	0.083	ppm
CF	22	0.142	0.064	ppm
CF	26	0.116	0.060	ppm
CF	30	0.113	0.060	ppm
CF	34	0.095	0.056	ppm
CF	38	0.066	0.039	ppm
CF	42	0.062	0.036	ppm
CF	46	0.075	0.039	ppm
CF	50	0.076	0.034	ppm
RF	2	9.08	<0.009	ppm



Sample ID	LS	Sr $\pm 0.003$	V $\pm 0.009$	Unit
RF	4	3.11	<0.009	ppm
RF	6	1.40	<0.009	ppm
RF	8	0.849	<0.009	ppm
RF	10	0.522	<0.009	ppm
RF	14	0.268	0.011	ppm
RF	18	0.174	<0.009	ppm
RF	22	0.135	<0.009	ppm
RF	26	0.117	<0.009	ppm
RF	30	0.135	<0.009	ppm
RF	34	0.115	<0.009	ppm
RF	38	0.085	<0.009	ppm
RF	42	0.075	0.011	ppm
RF	46	0.085	<0.009	ppm
RF	50	0.089	<0.009	ppm

**Table D21. Elemental concentrations of Zn  
(MDL = 0.010) in fly ash leachate.**

Sample ID	LS	Zn $\pm 0.010$	Unit
AF/C	2	<0.010	ppm
AF/C	4	<0.010	ppm
AF/C	6	<0.010	ppm
AF/C	8	<0.010	ppm
AF/C	10	<0.010	ppm
AF/C	14	<0.010	ppm
AF/C	18	<0.010	ppm
AF/C	22	<0.010	ppm
AF/C	26	<0.010	ppm
AF/C	30	<0.010	ppm
AF/C	34	<0.010	ppm
AF/C	38	0.010	ppm
AF/C	42	0.021	ppm
AF/C	46	0.036	ppm

Sample ID	LS	Zn $\pm 0.010$	Unit
AF/C	50	0.032	ppm
CF	2	0.022	ppm
CF	4	0.011	ppm
CF	6	<0.010	ppm
CF	8	0.014	ppm
CF	10	<0.010	ppm
CF	14	<0.010	ppm
CF	18	<0.010	ppm
CF	22	<0.010	ppm
CF	26	<0.010	ppm
CF	30	<0.010	ppm
CF	34	<0.010	ppm
CF	38	0.012	ppm
CF	42	<0.010	ppm
CF	46	<0.010	ppm
CF	50	<0.010	ppm
RF	2	1.24	ppm
RF	4	0.335	ppm
RF	6	0.134	ppm
RF	8	0.065	ppm
RF	10	0.034	ppm
RF	14	0.023	ppm
RF	18	0.031	ppm
RF	22	0.020	ppm
RF	26	0.017	ppm
RF	30	0.023	ppm
RF	34	0.019	ppm
RF	38	0.020	ppm
RF	42	0.016	ppm
RF	46	0.019	ppm
RF	50	0.013	ppm

## Appendix E: Elemental Concentrations in Sequential Extractions

This Appendix lists the concentrations of elements in the sequential extraction samples of bottom ash and fly ash. All leachate sample concentrations were determined by inductively coupled plasma analysis. Table E1 lists the sample codes used in Tables E2 through E32.

**Table E1. Sample identification codes.**

Sample ID codes	Meaning
AB	Abbott bottom ash
AF/C	Abbott fly/bottom ash combined
CB	Chanute bottom ash
CF	Chanute fly ash
RB	Rock Island bottom ash
RF	Rock Island fly ash
SQ#	Fraction number

**Table E2. Elemental concentrations (ppm) of Ag (MDL = 0.019).**

Sample ID	SQ1	SQ2	SQ3	SQ4
AB	<0.019	<0.019	<0.019	<0.019
AF/C	<0.019	<0.019	<0.019	<0.019
CB	<0.019	<0.019	<0.019	<0.019
CF	<0.019	<0.019	<0.019	<0.019
RB	<0.019	<0.019	<0.019	<0.019
RF	<0.019	<0.019	<0.019	<0.019

**Table E3. Elemental concentrations (ppm) of Al (MDL = 0.10).**

Sample ID	SQ1	SQ2	SQ3	SQ4
AB	0.41	33.8	47.1	103
AF/C	0.7	80.5	52	108
CB	0.37	18.2	21.3	36.4
CF	0.28	16	31.9	51.4
RB	1.06	17	26.6	40.7
RF	2.49	18.5	49.3	159

**Table E4. Elemental concentrations (ppm) of As (MDL = 1.65).**

Sample ID	SQ1	SQ2	SQ3	SQ4
AB	<1.65	<1.65	<1.65	<1.65
AF/C	<1.65	<1.65	<1.65	<1.65
CB	<1.65	<1.65	<1.65	<1.65
CF	<1.65	<1.65	<1.65	<1.65
RB	<1.65	<1.65	<1.65	<1.65
RF	<1.65	<1.65	<1.65	<1.65

**Table E5. Elemental concentrations (ppm) of B (MDL = 0.13).**

Sample ID	SQ1	SQ2	SQ3	SQ4
AB	0.18	3.02	1.2	1.04
AF/C	6.24	9.81	2.63	2.12
CB	1.11	1.63	0.89	0.43
CF	2.67	4.78	1.14	0.5
RB	0.55	0.57	0.49	0.32
RF	3.88	2.05	1.48	1.28

**Table E6. Elemental concentrations (ppm) of Ba (MDL = 0.003).**

Sample ID	SQ1	SQ2	SQ3	SQ4
AB	0.649	1	0.468	0.636
AF/C	0.364	2.83	0.919	1.59
CB	0.245	0.402	0.395	0.377
CF	0.228	0.463	0.659	0.558
RB	0.654	0.894	0.821	0.754
RF	1.21	1.44	1.02	1.92

**Table E7. Elemental concentrations (ppm) of Be (MDL = 0.001).**

Sample ID	SQ1	SQ2	SQ3	SQ4
AB	0.001	0.015	0.02	0.019
AF/C	0.001	0.077	0.046	0.036
CB	<0.001	0.027	0.033	0.026
CF	0.001	0.042	0.072	0.062
RB	0.001	0.008	0.018	0.017
RF	0.002	0.026	0.064	0.086

**Table E8. Elemental concentrations (ppm) of Ca (MDL = 0.14).**

Sample ID	SQ1	SQ2	SQ3	SQ4
AB	769	707	199	244
AF/C	975	925	129	144
CB	134	63.6	22.7	20.8
CF	280	104	16.1	12.2
RB	73.3	55.2	9.77	16.5
RF	90.1	26.2	21.1	29.9

**Table E9. Elemental concentrations (ppm) of Cd**  
**(MDL = 0.016(SQ4)..0.11(SQ1)).**

Sample ID	SQ1	SQ2	SQ3	SQ4
AB	<0.11	0.166	0.026	0.071
AF/C	<0.11	0.894	0.07	0.028
CB	<0.11	<0.030	<0.022	<0.016
CF	<0.11	0.034	<0.022	<0.016
RB	<0.11	<0.030	<0.022	<0.016
RF	<0.11	<0.030	<0.022	<0.016

**Table E10. Elemental concentrations (ppm) of Co (MDL = 0.044).**

Sample ID	SQ1	SQ2	SQ3	SQ4
AB	<0.044	0.059	0.059	0.072
AF/C	<0.044	0.152	0.072	0.059
CB	<0.044	0.114	0.139	0.327
CF	<0.044	0.267	0.197	0.351
RB	<0.044	0.029	0.071	0.044
RF	0.165	0.045	0.1	0.161

**Table E11. Elemental concentrations (ppm) of Cr**  
**(MDL = 0.021(SQ2)..0.068(SQ1)).**

Sample ID	SQ1	SQ2	SQ3	SQ4
AB	<0.068	0.162	0.183	0.269
AF/C	<0.068	0.762	0.338	0.274
CB	<0.068	0.075	0.284	0.075
CF	<0.068	0.104	0.138	0.1
RB	<0.068	0.048	0.068	0.04
RF	<0.068	0.064	0.099	0.248

Table E12. Elemental concentrations (ppm) of Cu (MDL = 0.007).

Sample ID	SQ1	SQ2	SQ3	SQ4
AB	<0.007	0.776	0.045	1.13
AF/C	<0.007	0.607	0.045	1.53
CB	<0.007	1.66	0.046	3.06
CF	<0.007	0.819	0.033	2.21
RB	<0.007	1.22	0.082	2.87
RF	<0.007	0.042	0.046	1.5

Table E13. Elemental concentrations (ppm) of Fe (MDL = 0.058).

Sample ID	SQ1	SQ2	SQ3	SQ4
AB	0.149	140	205	164
AF/C	0.577	109	299	153
CB	0.411	99.3	231	163
CF	0.274	111	265	179
RB	0.399	63.7	81.5	24.5
RF	2.32	36	67.2	56.7

Table E14. Elemental concentrations (ppm) of Hg (MDL = 0.46).

Sample ID	SQ1	SQ2	SQ3	SQ4
AB	<0.46	<0.46	<0.46	<0.46
AF/C	<0.46	<0.46	<0.46	0.46
CB	<0.46	<0.46	<0.46	<0.46
CF	<0.46	<0.46	<0.46	<0.46
RB	<0.46	<0.46	<0.46	<0.46
RF	<0.46	<0.46	<0.46	<0.46

Table E15. Elemental concentrations (ppm) of K (MDL = 2.8).

Sample ID	SQ1	SQ2	SQ3	SQ4
AB	10.4	6.7	<2.8	9.9
AF/C	126	36.4	<2.8	14.7
CB	9.22	<2.8	<2.8	6.2
CF	7.39	<2.8	<2.8	6
RB	11.8	<2.8	<2.8	7.3
RF	36.8	<2.8	<2.8	21.7

Table E16. Elemental concentrations (ppm) of Li (MDL = 0.007).

Sample ID	SQ1	SQ2	SQ3	SQ4
AB	0.045	0.055	0.041	0.038
AF/C	0.258	0.168	0.049	0.043
CB	0.472	0.191	0.148	0.096
CF	0.245	0.154	0.085	0.076
RB	0.296	0.166	0.198	0.125
RF	1.42	0.178	0.122	0.23

Table E17. Elemental concentrations (ppm) of Mn (MDL = 0.009).

Sample ID	SQ1	SQ2	SQ3	SQ4
AB	0.02	13.5	3.78	1.62
AF/C	0.345	15.8	4.25	1.24
CB	0.069	2.54	1.23	0.358
CF	0.01	3.8	0.704	0.234
RB	0.199	1.24	0.502	0.094
RF	0.606	0.508	0.271	0.211



**Table E18. Elemental concentrations (ppm) of Mo**  
(MDL = 0.084(SQ4)..0.22(SQ1)).

Sample ID	SQ1	SQ2	SQ3	SQ4
AB	<0.22	<0.09	<0.16	0.146
AF/C	0.29	<0.09	<0.16	0.459
CB	<0.22	<0.09	<0.16	<0.084
CF	<0.22	<0.09	<0.16	<0.084
RB	<0.22	<0.09	<0.16	<0.084
RF	<0.22	<0.09	<0.16	0.328

**Table E19. Elemental concentrations (ppm) of Na (MDL = 0.22).**

Sample ID	SQ1	SQ2	SQ3	SQ4
AB	9.01	-	-	-
AF/C	196	-	-	-
CB	2.91	-	-	-
CF	3.66	-	-	-
RB	0.83	-	-	-
RF	12.1	-	-	-

**Table E20. Elemental concentrations (ppm) of Ni**  
(MDL = 0.072(SQ4)..0.17(SQ1)).

Sample ID	SQ1	SQ2	SQ3	SQ4
AB	<0.17	0.55	0.196	0.501
AF/C	<0.17	1.19	0.223	0.176
CB	<0.17	0.65	0.479	0.931
CF	<0.17	1.75	0.637	1.38
RB	<0.17	0.11	0.093	0.076
RF	<0.25	<0.10	0.109	0.25

**Table E21. Elemental concentrations (ppm) of P**  
(MDL = 0.52(SQ4)..2.45(SQ1)).

Sample ID	SQ1	SQ2	SQ3	SQ4
AB	<2.45	3.46	3.54	56
AF/C	<2.45	1.34	2.99	30.9
CB	<2.45	1.4	0.96	1.23
CF	<2.45	3.13	2.6	3.69
RB	<2.45	<0.66	0.94	1.11
RF	<2.45	0.99	1.43	4.63

**Table E22. Elemental concentrations (ppm) of Pb**  
(MDL = 0.11(SQ3)..0.59(SQ1)).

Sample ID	SQ1	SQ2	SQ3	SQ4
AB	<0.59	<0.17	0.28	<0.13
AF/C	0.68	0.39	0.42	<0.13
CB	<0.59	0.18	0.29	<0.13
CF	<0.59	0.78	0.35	<0.13
RB	<0.59	0.18	<0.11	<0.13
RF	<0.59	0.31	0.29	<0.13

**Table E23. Elemental concentrations (ppm) of S (MDL = 0.98).**

Sample ID	SQ1	SQ2	SQ3	SQ4
AB	99.2	12.9	6.21	74.8
AF/C	876	52.6	7.72	52.5
CB	12.7	2.28	5.35	64.5
CF	30.7	5.31	5.84	67.4
RB	9.05	1.86	5.08	15.8
RF	113	10.9	4.85	19.1

**Table E24. Elemental concentrations (ppm) of Sb**  
**(MDL = 1.0(SQ2)..1.8(SQ4))**

Sample ID	SQ1	SQ2	SQ3	SQ4
AB	<1.65	<1.0	<1.06	<1.8
AF/C	<1.65	<1.0	<1.06	<1.8
CB	<1.65	<1.0	<1.06	<1.8
CF	<1.65	<1.0	<1.06	<1.8
RB	<1.65	<1.0	<1.06	<1.8
RF	<1.65	<1.0	<1.06	<1.8

**Table E25. Elemental concentrations (ppm) of Se**  
**(MDL = 0.43(SQ2)..1.20(SQ1))**

Sample ID	SQ1	SQ2	SQ3	SQ4
AB	<1.20	<0.43	<0.88	<0.63
AF/C	<1.20	<0.43	<0.88	<0.63
CB	<1.20	<0.43	<0.88	<0.63
CF	<1.20	<0.43	<0.88	<0.63
RB	<1.20	<0.43	1.04	<0.63
RF	<1.20	<0.43	<0.88	<0.63

**Table E26. Elemental concentrations (ppm) of Si (MDL = 0.14).**

Sample ID	SQ1	SQ2	SQ3	SQ4
AB	1.63	116	55.9	133
AF/C	3.85	143	51.7	105
CB	4.24	25	23.8	33.5
CF	1.53	30.7	33.9	41.1
RB	4.55	13.3	17.4	30.3
RF	2.86	12.5	25.9	59.9

**Table E27. Elemental concentrations (ppm) of Sn**  
**(MDL = 0.14(SQ2)..0.49(SQ1)).**

Sample ID	SQ1	SQ2	SQ3	SQ4
AB	<0.49	<0.14	0.56	<0.22
AF/C	<0.49	<0.14	0.53	<0.22
CB	<0.49	<0.14	0.49	<0.22
CF	<0.49	<0.14	0.46	<0.22
RB	<0.49	<0.14	1.85	<0.22
RF	<0.49	0.18	0.48	<0.22

**Table E28. Elemental concentrations (ppm) of Sr (MDL = 0.001).**

Sample ID	SQ1	SQ2	SQ3	SQ4
AB	1.24	1.54	0.921	0.965
AF/C	1.53	2.21	0.764	0.803
CB	0.645	0.593	0.639	0.635
CF	0.577	0.572	1	0.805
RB	0.398	0.295	0.689	0.883
RF	2.15	1.1	2.35	2.92

**Table E29. Elemental concentrations (ppm) of Ti (MDL = 0.007).**

Sample ID	SQ1	SQ2	SQ3	SQ4
AB	0.02	0.619	0.33	7.07
AF/C	0.036	0.471	0.275	12.5
CB	0.032	0.175	0.14	4.46
CF	0.027	0.242	0.49	4.62
RB	0.052	0.163	1.175	3.89
RF	0.006	0.21	0.378	10.5

**Table E30. Elemental concentrations (ppm) of Ti  
(MDL = 1.0(SQ4)..3.0(SQ1)).**

Sample ID	SQ1	SQ2	SQ3	SQ4
AB	<3.0	<1.1	<1.84	<1.0
AF/C	<3.0	<1.1	<1.84	<1.0
CB	<3.0	<1.1	<1.84	<1.0
CF	<3.0	<1.1	<1.84	<1.0
RB	<3.0	<1.1	<1.84	<1.0
RF	<3.0	<1.1	<1.84	<1.0

**Table E31. Elemental concentrations (ppm) of V (MDL = 0.036).**

Sample ID	SQ1	SQ2	SQ3	SQ4
AB	<0.036	0.056	0.292	0.363
AF/C	<0.036	<0.036	0.596	0.545
CB	<0.036	<0.036	0.272	0.207
CF	<0.036	<0.036	0.313	0.33
RB	<0.036	0.068	0.495	0.333
RF	<0.036	0.105	1.09	2.44

**Table E32. Elemental concentrations (ppm) of Zn (MDL = 0.034).**

Sample ID	SQ1	SQ2	SQ3	SQ4
AB	<0.034	20.6	1.17	6.63
AF/C	<0.034	34.3	2.87	2.96
CB	<0.034	1.37	0.229	0.305
CF	<0.034	2.72	0.181	0.514
RB	<0.034	0.713	0.102	0.109
RF	<0.528	0.497	0.157	0.254

## Appendix F: State Regulations Concerning Coal Ash Disposal

**Table F1. State regulations governing coal ash disposal/utilization (non-scrubber ash).**

State	Coal Specific	Ash Test	Disposal Methods
Alabama	N	N	15,23 (Unregulated for other use)
Alaska	N	N	15,23,2
Arizona	Y	N	20,23
Arkansas	N	N	15,2,24
California	N	Y	2
Colorado	N	N	1,2
Connecticut	N	N	15,3,19
Delaware	Y	Y	15,21
Florida	N	N	ANY
Georgia	N	N	24
Idaho	N	N	24
Illinois	Y	Y	23,14
Indiana	Y	Y	15,23,2

**Codes:**

1. New coal specific regulations planned.
2. Any use on a case-by-case review.
3. Any use in/on concrete/cement/asphalt.
4. Fill base.
5. Mineral recovery.
6. Gypsum Source.
7. Active mine disposal.
8. Paint.
9. Plastics.
10. Anti-skid material.
11. Highway base course.
12. Blasting grit.
13. Roofing granules.
14. Mine stabilization.
15. Municipal landfill.
16. Soil improvement.
17. Agriculture.

18. Soil conditioning.
19. Land reclamation.
20. Special landfill.
21. Other products.
22. Not specified.
23. On-site landfill.
24. Same as Federal (EPA CFR 40), ...fly ash, bottom ash, coal-boiler slag, and flue gas emission control waste are excluded from hazardous waste designation.... Source: EPA CFR 40-261.4.(b)(4) (promulgated July 1, 1992). Most states which use this ruling require that the ash from a facility be tested using the TCLP only when permits are initially obtained for the plant or during landfill/other use permit processes. After that time, no other testing is required unless some major change in the coal source or process operation is made. When the ash is reused, it is not classified as solid waste (FED.EPA CFR40PRT260-270).

State	Coal Specific	Ash Test	Disposal Methods
Iowa	Y	N	15,23,3,4,5,6
Kansas	N,1	N	15
Kentucky	Y	N	20
Louisiana	Y	Y	2,3,11,20
Maine	N	Y	15
Maryland	Y	N	4,5,7 Through 14
Massachusetts	Y	N	ANY (With proper permits)
Michigan	N	N	24
Minnesota	N	Y	15,20
Mississippi	N	N	24
Missouri	N	Y	ANY (If ash passes TCLP test)
Montana	Y	Y	2,3,4,6,10,11,15,23
Nebraska	Y	N	20
Nevada	N	N	15,23
New Hampshire	Y	Y	2,20
New Jersey	Y	Y	2,4,21
New Mexico	N	N	24
New York	N	Y	15,3,10,2
North Carolina	Y	Y	ANY (If ash passes TCLP test)
North Dakota	N	N	22
Ohio	N	N	15,2

## Codes:

1. New coal specific regulations planned.
2. Any use on a case-by-case review.
3. Any use in/on concrete/cement/asphalt.
4. Fill base.
5. Mineral recovery.
6. Gypsum Source.
7. Active mine disposal.
8. Paint.
9. Plastics.
10. Anti-skid material.
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12. Blasting grit.
13. Roofing granules.
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15. Municipal landfill.
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State	Coal Specific	Ash Test	Disposal Methods
Oklahoma	N	N	15
Oregon	N	N	24
Pennsylvania	Y	Y	3,4,5,7,10,11,14,18,19
Rhode Island	N	N	24
South Carolina	N	Y	20
South Dakota	N	N	15,2
Tennessee	Y	N	15,4,2
Texas	N	N	24
Utah	N	N	ANY (on list below)
Vermont	N	N	15
Virginia	Y,1	N	ANY (on list below)
Washington	Y	N	15,20,2 (Regulated by the county)
Washington, D.C.	N	N	24
West Virginia	Y	Y	3,4,10,11,15,23,21
Wisconsin	Y	N	15,23,3,11,2
Wyoming	N	N	20 (Industrial landfills)

## Codes:

1. New coal specific regulations planned.
2. Any use on a case-by-case review.
3. Any use in/on concrete/cement/asphalt.
4. Fill base.
5. Mineral recovery.
6. Gypsum Source.
7. Active mine disposal.
8. Paint.
9. Plastics.
10. Anti-skid material.
11. Highway base course.
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